Scientia

SCIENTIFIC SOLUTIONS FOR SUSTAINABLE AGRICULTURE

HIGHLIGHTS:

- Resilient Cropping Systems for a Sustainable Future
- The Role of Policies in Managing Scarce Water Resources
- Investigating the Role of Land Use in Climate Change
- Working Together to Achieve a Better Future for the Horticultural Industry

Issue: #123

WELCOME...

In this important edition of Scientia, we address one of the greatest challenges of our time – ensuring food security and agricultural sustainability into the future. Here, we feature a broad range of promising research projects – from protecting pollinators to conserving irrigation water in the face of climate change, and from improving soil health to understanding what motivates anglers to target bluefin tuna.

Our first section of the edition focuses on crop science, where we introduce a diverse collection of initiatives, each striving to make our cropping systems more sustainable and to improve yields in the face of climate change. Here, we show how focusing on biodiversity and ecosystem services can actually help to improve agricultural yields. We can also read how targeted pest control, using cutting-edge genetic tools, can help to reduce damage to crops without causing collateral damage to bees and other pollinators.

Next, we move on to another important consideration in achieving food sustainability – water conservation. With climate change both diminishing our water resources while increasing our demand for water, finding scientific solutions for water conservation is now more important than ever before. As about 70% of all our freshwater withdrawals are used for agricultural purposes, meeting our growing population's increasing food demands is set to become increasingly difficult in the decades to come.

The subsequent section deals with devising and informing land management strategies to ensure sustainability and restore biodiversity. Here we read about effective approaches to eradicate invasive species, and how land usage can affect the local climate. We also explore how different land management practices can help to boost soil health in pastureland.

Our final section of the edition takes a different view on food security and sustainability – providing a perspective on the role human behaviour and sociology in these issues. Here, we explore how a thorough understanding of the behaviours and attitudes of both food producers and consumers must be achieved in order to ensure food security into the future.

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CONTACT

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E: info@sciencediffusion.com
W: www.sciencediffusion.com
W: www.scientia.global

@scientia_social
www.facebook.com/socialscientia
www.linkedin.com/company-beta/11065635

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CROP SCIENCE

HOLISTIC APPROACHES TO SUSTAINABLE CROP PRODUCTION

Our agriculture takes up almost 40% of Earth's total land area, or about half of all habitable land on the planet. This has led to widespread deforestation and habitat destruction worldwide, thus significantly contributing to global biodiversity decline. A whopping 77% of this agricultural land is taken up by livestock, even though meat and dairy products comprise only 17% of our calorie supply and just a third of our protein intake. Therefore, drastically reducing our consumption of animal products would allow us to return an extensive amount of land back to nature, in addition to reducing the greenhouse gas emissions and animal welfare concerns associated with livestock farming.

However, with most of our current methods of growing crops, going vegan is not as sustainable as one might think. Such intensive and unsustainable crop production represents a huge threat to the environment and global biodiversity, due to the use of toxic pesticides and herbicides, water contamination and soil erosion. As one example, according to the Food and Agriculture Organization, all of the world's topsoil could be gone in about 60 years, if we continue to erode soil at the current rate.

Therefore, agricultural scientists are working hard to develop more sustainable methods of growing crops. Such sustainable agricultural systems can actually help to preserve and restore ecosystems, and actually improve soil health and water quality.

Improving our agricultural yields is another consideration, as increased efficiency means a reduced demand for land. This can be achieved through tackling crop diseases in a targeted fashion or developing crop varieties that are resistant to pests or extreme weather. Indeed, the extreme weather brought on by climate change is becoming an increasing problem to our global food supplies, as most cropping systems are vulnerable to droughts, storms, flooding, heatwaves and the increased numbers of pathogens that often accompany temperature rises.

Clearly, research in this area is now more important than ever before. Therefore, sustainable crop production is the theme of our first section of this edition, where we showcase the latest innovations in crop science. To open this section, we introduce Dr Rajan Ghimire, from New Mexico State University's Agricultural Science Center, who focuses on improving the sustainability and resilience of cropping systems and optimising associated farming practices. His team develops practical solutions to crop production that restore soil health, improve environmental quality and even mitigate climate change.

Also building more eco-friendly and resilient cropping systems is Dr Amélie Gaudin at the University of California, Davis. Her team develops multifunctional agricultural systems where biodiversity and ecosystem services serve as a basis for the improvement of crop production. This holistic approach offers exciting opportunities to improve resilience and maintain agricultural sustainability in the face of climate change. Like Dr

Ghimire, one of Dr Gaudin's research focuses explores how healthier soils can increase the resilience of agroecosystems to stresses, such as those posed by climate change.

Soil health is also a major focus of our next featured researcher – Dr Ermita Hernandez at the University of Puerto Rico. Here, we introduce her team's work in identifying the most sustainable, low-input management protocols for growing tomato and sweet pepper crops in Puerto Rico. Through thorough experimentation, Dr Hernandez's team assesses the effects of various practices on soil health – including the use of cover crops and adding organic compost to soils.

Continuing on the theme of sustainable crop production in Puerto Rico, our next article in this section showcases research into one of the island's (and indeed the world's) most important starchy crops – the yam. Here, we meet Dr Merari Feliciano-Rivera, also at the University of Puerto Rico, who develops new techniques to minimise yam yield losses. Her team has already begun to characterise the causal agents behind several devastating diseases and develop management techniques towards sustainable yam production.

Next, we introduce the work of Dr Paul Tseng and his research group at Mississippi State University, who aim to improve the resilience of rice crops by incorporating competitive traits from weeds into them. Most modern rice varieties are composed of almost identical individual plants, meaning that they lack genetic diversity and are ill-adapted to changing environmental conditions – such as those associated with climate change. 'Weedy rice' varieties, on the other hand, have incredible genetic diversity, and thus possess remarkable adaptations to harsh environments – exactly what our crops need to survive in times of climactic change. By characterising the genetic basis of weedy rice's competitive traits, Dr Tseng's team hopes to pave the way for the development of resilient and sustainable rice varieties.

On the topic of resilience, one remarkable trait that many plants possess is the ability to survive freezing. With severe weather events on the rise, including extreme cold snaps, the ability to survive freezing is a highly desirable trait for crops. Therefore, Dr David Livingston and Dr Michael Wisniewski of the US Department of Agriculture have been investigating these freezing mechanisms in great detail, with the help of remarkably intricate imaging techniques. In the future, the researchers hope to use their insights to identify genetic traits that can be used to select and develop high-yielding, freezing-tolerant crops.

In addition to the extreme weather that climate change brings, the increased carbon dioxide in the atmosphere that drives such change can itself negatively affect the quality of our crops. This is just one of many research directions explored by Dr Rajashekar and his team at Kansas State University, who we meet in the next article of this section. Specifically, the team

examined the impact of elevated carbon dioxide levels on the nutritional quality lettuce and spinach crops, finding that elevated carbon dioxide decreases the concentration of several key nutrients.

The warmer temperatures caused by elevated atmospheric carbon dioxide also allow many plant pathogens and pests to proliferate and spread more easily than before. Therefore, our next four articles deal with finding ways to tackle plant diseases and pests. First, we meet Drs Fred Gmitter, Zhanao Deng and Yi Li of the University of Florida and the University of Connecticut, who are finding ways to curb Huanglongbing (HLB), a devastating bacterial disease that affects citrus trees. Using the insights gained in their research, the team aims to develop resistance to HLB in citrus plants, using conventional breeding and cutting-edge CRISPR gene-editing approaches.

We then shift our attention to viruses that infect crops. Here, we meet Dr Hernan Garcia-Ruiz and his team at the University of Nebraska, who identify cellular factors that cause plants to be susceptible to various devastating viruses. Through elucidating the mechanisms that allow a plant to recognise the presence of a virus, the team hopes to engineer virus resistance in crops.

Also aiming to develop resistance in crops is Dr Gerald Reeck and his team at Kansas State University. However, rather than creating resistance towards a bacterial or viral pathogen, Dr Reeck focuses on aphids – a serious agricultural pest. In the next article of this section, we introduce his team's insights into aphid and plant biology, which he hopes will lead to improved and targeted strategies to control aphid infestations of crops.

Next, we meet Dr Paul Dyson, Dr Miranda Whitten and their colleagues at Swansea University, who are pioneering a new technology known as 'symbiont-mediated RNA interference' to control infestations of agricultural pests.

By developing this highly-targeted method, which exploits symbiotic bacteria found inside insects, the team hopes to reduce the dependence of global agriculture on insecticides, which can be very harmful to bees and other pollinators.

Indeed, global populations of bees are steadily declining – with worrying implications for global agriculture, since many of our crops rely on bees to produce fruit and reproduce. Therefore, our final article of this section describes fascinating research into the intricacies of bee-flower interactions. Here, we meet Dr Johanne Brunet and her team at the USDA-Agricultural Service, whose insights into how different bees forage in crop fields will help to promote bee survival and conservation.

SUSTAINABLY FEEDING CURRENT AND FUTURE GENERATIONS

Sustainable food production in an ever-changing climate is high on the global agenda. **Dr Rajan Ghimire** from New Mexico State University is part of a community of scientists who aim to improve agricultural practices for greater crop resilience and long-term sustainability. Specifically, he focuses on improving the efficiency of agroecosystems through improved tillage, crop rotations, crop residues, and soil health management practices.

Sustainable Farming Practices

Access to life's necessities, such as food and clean water, is as important as ever. Of course, the success of food production is highly dependent on climate conditions. Climate change is already influencing soil health and crop production around the world. This is compounded, in many cases, by dwindling water resources. However, better agricultural management practices can go a long way to mitigating, and even eliminating, some of these effects. Sustainable farming practices may also reduce global greenhouse gas emissions and help reverse some of the effects of climate change.

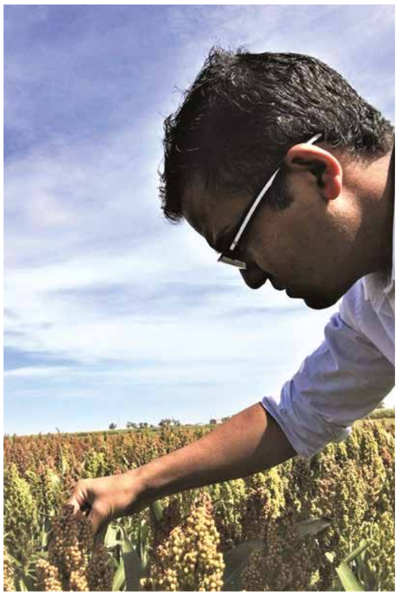
With little wonder then, scientists are working hard to improve current farming practices – ensuring that they not only provide what we need as a human race, but that they are also sustainable and environmentally friendly. Dr Rajan Ghimire, from New Mexico State University's Agricultural Science Center is one such scientist. His team's work focuses on improving the sustainability and resilience of agroecosystems and optimising associated farming practices, especially as applied to the semi-arid regions of New Mexico, where soil health and fertility are declining.

'Climate change and its impacts on agricultural sustainability could not be more evident than in the semiarid agroecosystems with inherently low fertility soils and highly variable climate typical in the western parts of the United States,' says Dr Ghimire. 'It calls for immediate action to develop practical and profitable solutions to cropping systems management that restores soil health, improve environmental quality, and mitigates global warming with efficient use of the limited water available for crop production.'

Motivated by this reality, Dr Ghimire's research aims to develop practical and profitable solutions for managing cropping systems in a way that restores soil health and makes the best use of the limited water available for crop production. Central to achieving this goal is better tillage practices, crop rotations and enhanced carbon sequestration from crop residues.

Addressing the Decline in Soil Organic Carbon

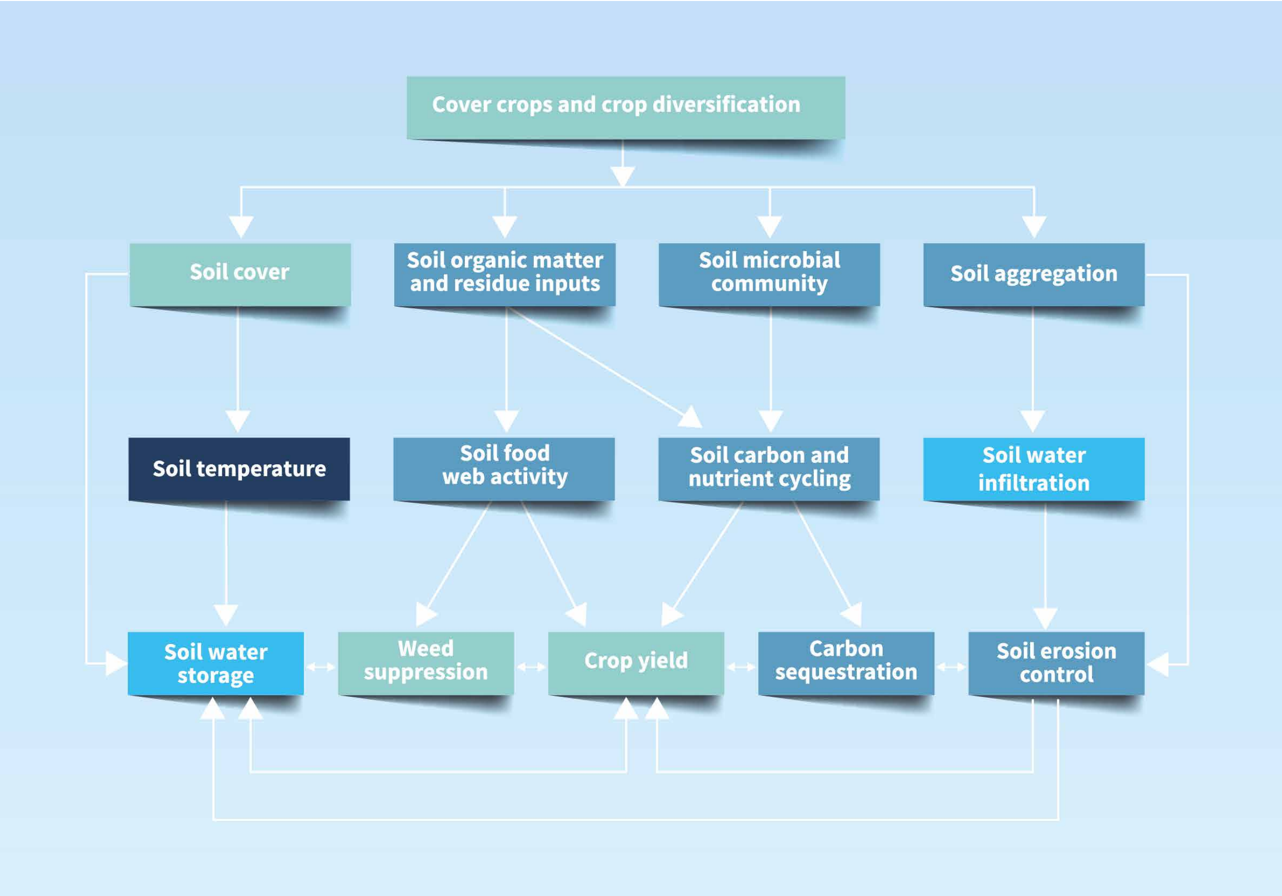
Carbon sequestration refers to the process of taking carbon from the atmosphere (as carbon dioxide) and converting into a form that can be stored long-term. Carbon sequestration is part of the carbon cycle – a fine-tuned process that ensures carbon is recycled



and reused. Plants, and thus crops, have a large role to play in sequestering carbon into the soil.

Soil organic carbon (SOC) refers to the carbon that is contained within soil organic matter. SOC is said to be the basis for soil health and agroecosystem resilience as it is associated with the provision of nutrients and maintaining soil structure. Higher soil organic matter, which correlates with higher SOC, is also needed to retain moisture and reduce soil erosion. The levels of

‘Climate change and its impacts on agricultural sustainability could not be more evident than in the semiarid agroecosystems with inherently low fertility soils and highly variable climate typical in the western parts of the United States… It calls for immediate action to develop practical and profitable solutions to cropping systems management that restores soil health, improve environmental quality, and mitigates global warming with efficient use of the limited water available for crop production.’



SOC can be an indicator of soil health, and the potential for crops to succeed. Therefore, scientists and farmers alike are searching for alternative management practices to increase SOC accumulation that are both effective and sustainable.

Understanding the rate of SOC mineralisation and incorporation into the soil is vital in this regard. Dr Ghimire specifically focuses on the sequestration of carbon into the soil from crop ‘residues’. The term ‘residue’ simply refers to the material that is left behind after a crop is harvested. Commenting on the practice, Dr Ghimire stated that ‘crop residues are the main input in maintaining SOC and nutrients in agricultural soils.’

Dr Ghimire and his colleagues studied the rate of carbon sequestration in residues of pea, oat and canola cover crops (crops grown to enrich the soil). They subsequently collected soil samples from these fields and estimated the rates of soil carbon turnover, that is, the rate of carbon intake against carbon loss. The team also determined the concentrations of target SOC fractions – those that facilitate nutrient cycling and support crop production.

As one might expect, where more residue was left behind, the concentration of labile SOC increased. The rate at which carbon sequestration occurred also increased. However, the team noticed that the latter tended to vary depending on the type of cover crop used. Nevertheless, it was clear that crop residues are indeed useful for sequestrating carbon into agricultural soils – a useful piece of knowledge for developing more sustainable farming practices.

As Dr Ghimire relates, although cover crops are dependent on precipitation and the availability of water for irrigation, they ‘can help in optimising resource use and conservation while maintaining agronomic, environmental, and economic goals of sustainable farming.’ Cover crops also serve to improve soil health and can result in better yields for the following crop.

Achieving Sustainable Agrobiodiversity

Understanding the impacts of different crops on farmland is critical to improving management processes. In addition to this, understanding the stresses that crops experience in a changing climate and growing regionally-appropriate crops can improve the sustainability and profitability. In fact, this was the subject of a recent literature review that Dr Ghimire and his colleagues conducted, and is also the focus of the team's ongoing research. There are several interesting findings from the review.

For one thing, Dr Ghimire stressed that 'diversification of cropping systems is critical for improving agricultural sustainability in semiarid regions like New Mexico because soil health and fertility in the region are largely associated with farming practices that focus more on short-term profits at the expense of long-term soil and environmental quality.' For example, Dr Ghimire and his team found that corn and wheat crops, although useful in many different applications, are potentially unsustainable as their resilience significantly decreases when they are subjected to environmental stressors. Therefore, alternatives to corn and wheat are worth considering, especially in a changing climate.

Dr Ghimire and his team also found that crop rotation and diversification have the potential to enhance SOC in agricultural soils and the resilience of cropping systems. Further benefits of these techniques include reducing greenhouse gas emissions from farmland and reducing the pollution of local waterways from agricultural run-off. However, crop rotation alone may take several years to enhance SOC levels in the soil. Rather, it is better to combine crop rotation with reduced tillage management (tillage refers to the process of preparing the land for growing crops) and other soil conservation measures. The good news is, these techniques are progressively being integrated into farming practices.

Water-Saving Farming Practices

The Ogallala aquifer is the most economically important groundwater source in eastern New Mexico and is the primary driver for crop production in the High Plains region. Sadly, water levels in the New Mexico portion of the Ogallala have been in a long-term, serious decline for decades. Therefore, sustainable management of the resource, that is, ensuring that recharging of the aquifer exceeds extraction, is vital.

Dr Ghimire suggests that altering tillage practices is one potential solution. In one report, he stated that 'research on conventional tillage, strip-tillage, and no-tillage comparison in dryland situations shows the many benefits of reducing tillage. Specifically, no-tillage in dryland corn-sorghum rotations has increased soil water storage, reduced soil erosion, and maintained comparable crop yields.'

Of course, a different approach to tillage isn't the only solution. Cover crops, crop rotation and diversification, and the input of biomass carbon have also been effective in increasing water use efficiency in New Mexico. Introducing more water efficient crops in rotation may increase economic returns for farmers while maintaining soil health and improving the environment. In fact, Dr Ghimire and his team are very much concerned with the sustainable use of water for crop production. In collaboration with other scientists from other states, for example, he has been working in the Ogallala aquifer region on improving water use efficiency and adopting water conservation practices.

Meeting Our Needs in a Changing Climate

Dr Ghimire's work is focused on meeting our food production needs, whilst minimising our impact on the environment and ensuring the long-term environmental and economic sustainability of global agriculture. Of course, this will be an ongoing challenge, especially as Earth's climate continues to undergo significant change and more demands are placed upon global food markets.

Nevertheless, Dr Ghimire is committed to this cause. He will continue to work on agricultural conservation practices, a systems approach to research, real-world implementation of research outcomes, and the efficiency, profitability, and environmental quality of farming systems. Ultimately, he hopes to improve overall soil health, reduce greenhouse gas emissions from farming land, and improve water use and conservation efficiency. Indeed, Dr Ghimire is working towards adequately feeding current and future generations – in a sustainable and environmentally friendly way.

Meet the researcher

Dr Rajan Ghimire
New Mexico State University
Agricultural Science Center
Clovis, NM
USA

Dr Rajan Ghimire received his PhD in soil science from the University of Wyoming in 2013. At present, he serves as Assistant Professor at the New Mexico State University's Agricultural Science Center at Clovis. His research has focused on improving the agronomic, economic, and environmental efficiency of agroecosystems through improved tillage, crop rotations, crop residues, and soil fertility management practices. He has actively participated in professional societies such as the American Society of Agronomy (ASA), the Soil Science Society of America (SSSA), and the American Association for Advancement of Science (AAAS). Ultimately, his goal is to ensure the long-term economic and environmental sustainability of agriculture.

CONTACT

E: rghimire@nmsu.edu
W: http://aces.nmsu.edu/directory/person.php?person_id=2045

KEY COLLABORATORS

Dr Mark Marsalis, Dr Omololu J Idowu, Dr Sangu Angadi, Dr Abdel Mesbah, Dr Ram N. Acharya, NMSU
Dr Meagan Schipanski, CSU
Dr Veronica Acosta-Martinez, Dr Upendra Sainju, USDA-ARS

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RESILIENT CROPPING SYSTEMS FOR A SUSTAINABLE FUTURE

Dr Amélie Gaudin at the University of California, Davis explores ways to develop more efficient and resilient cropping systems. Here we take a closer look at just a few of Dr Gaudin's research projects, which aim to build multifunctional agricultural systems where biodiversity and ecosystem services serve as a basis for improvement. Her comprehensive approach to management offers exciting opportunities to improve resilience and maintain agricultural sustainability in a time of climatic change.

Modern farming practices employ improved varieties and intensive practices on specialised farms and landscapes to maximise yields. Agricultural production accelerated dramatically during the 'Green Revolution' of the 1970s, and farmers were urged to mechanise and use chemical fertilisers and pesticides to intensify their production. While productivity increased at an astonishing rate, such farming systems are often not sustainable, are vulnerable to climate change, and put the ecosystems they are dependent on at risk.

In contrast, an alternative approach places emphasis on ecological intensification, which allows ecosystem services to flourish to decrease dependence on inputs. In this approach, value is placed on a system's ability to efficiently cycle and use resources, foster healthy soils, and contribute to clean water. The field of agroecology aims to understand the complex ecological processes at play in an agroecosystem and apply this knowledge to the design and management of production systems. In essence, agroecology helps to develop management systems that function more like the ecosystem that agriculture replaced.

Dr Amélie Gaudin and her team, in the Department of Plant Sciences at the University of California, Davis use agroecological principles to develop management strategies that intensify ecological processes to decrease input needs and decrease the environmental footprint of agriculture.

Focusing on whole systems rather than on specific crops, and integrating outreach and education activities, Dr Gaudin brings together a pioneering partnership of growers, agronomists, breeders and industry stakeholders. This comprehensive approach to management offers exciting new opportunities to build both the sustainability and resilience of agroecosystems.

Diversification is Key

One main research theme explored by Dr Gaudin and her team is the impact of diversification strategies and healthier soils on resilience of agroecosystems

to stress. These stressors can be both biotic (relating to or resulting from living organisms, such as insects) or abiotic (physical rather than biological, such as drought). By placing emphasis on soil health, Dr Gaudin's approach takes into account a soil's capacity to function as a vital living ecosystem.

Indeed, increasing an agroecosystem's diversity is a key strategy for coping and adapting to climate change. Greater diversity, especially the use

of complex crop rotations over time (temporal diversity) is thought to lead to more stable ecosystems, thanks to functional redundancies and improved conservation and access to soil resources by crops. Dr Gaudin and her colleagues set out to test this hypothesis across various extremely valuable agroecosystems, from temperate rainfed maize of the Midwest to irrigated semi-arid tomato production systems of California. Their aim is also to better understand the underlying mechanisms to inform management and enhance sustainable food production under abiotic stresses.

The research team first undertook retrospective analysis of historical data from a 31-year long-term rotation and tillage trial to explore the impact of temporal diversity (rotation) and reduced disturbance (tillage) on resilience of maize and soybean systems in the northern Corn Belt, Ontario, Canada. This region was once prairie, but over the past 30 years has experienced large decreases in agroecosystem diversity – small grain cereals have been progressively replaced by rows of soybeans and corn, which now dominate the landscape. Dr Gaudin's study is the first to quantify the impact of management practices on yield stability, particularly when exposed to extreme weather events (drought or flooding).

Dr Gaudin and her team validated the hypothesis that crop yield stability significantly increases when corn and soybean are integrated into more diverse rotations. They found that introducing small grains into short corn-soybean rotation provided significant benefits on long-term soybean yields. Crop diversification increased the likelihood of harnessing favourable growing conditions, and decreased the risk of crop failure. In hot and dry years, diversification of corn-soybean rotations and reduced tillage increased yields by 7% (for corn) and 22% (for soybean).

Exploring the underlying mechanisms, Dr Gaudin gives compelling evidence that complex rotations and reduced disturbance have a synergistic effect – where the collective effect provides greater benefit than separate effects combined. In a similar study on irrigated tomato crops, Dr Gaudin and her colleagues are now exploring the ways in which more diversified systems show significant yield resilience over time and when lower levels of irrigation are applied. Such an approach takes advantage of better soil health to conserve costly and finite water supplies.

The team's recent findings show that rotation complexity provides a systems approach to help adapt agroecosystems to changes in crop growing conditions. This approach could help to sustain future yields under increasingly difficult production environments, by making farming systems more resilient to environmental stress.

Amazing Grazing

Another strategy to increase diversification explored by Dr Gaudin and her team is the impact of reintegrating livestock into cropland. Dr Gaudin investigates how land-based livestock integration and manure amendments impact resilience and sustainability of dairy forage and viticulture cropping systems – both huge industries in California.

Traditional agricultural systems commonly combined livestock production with crop rotations. However, modern industrial agriculture methods that incentivise specialisation and economies of scale have moved towards decoupling crop and livestock production, resulting in concerns over water quality, agriculture's high carbon footprint and poor soil health.

Could re-integrating crop and livestock systems at the field and farm level help reduce inputs while increasing yields? What are the main barriers to adoption? This question is posed by Dr Gaudin in a recent publication, highlighting many knowledge gaps associated with both social and ecological aspects of integrated crop and livestock systems. She and others advocate for transdisciplinary and collaborative research efforts to address these gaps and inform effective reintegration.

California, which has extremely diverse cropping systems, provides promising opportunities for this reintegration. Dr Gaudin's own research investigates the impacts of sheep grazing on soil health and the sustainability of annuals and vineyard production systems in California. Dr Gaudin and her research partners also seek to understand changes in the long-term stability and resilience of primary production of soybean with greater cattle livestock integration in Brazil.

Using Soil Science to Control Pests

The Gaudin lab also explores strategies that build resilience to pests. The team recently discovered that soil and rhizosphere microbes are instrumental to building up plant defences against herbivores, especially insects, which can carry major viruses. For instance, tomato crops in California are vulnerable to the beet leafhopper, which carries a damaging virus that negatively impacts crop yields. Dr Gaudin and her collaborators aim to understand the potential of organic soil management practices to decrease infestation of leafhoppers. Intriguingly, the microbes at the plant root surface (the rhizosphere) play an instrumental role in this process.

Their research has revealed that soil-health building management practices, such as compost and cover crops, affect tomato attractiveness to beet leafhoppers and can therefore potentially reduce virus incidence. Understanding these mechanisms better, especially in the rhizosphere, can help us use this knowledge to breed for below-ground characteristics that improve soil health and plant resilience to multiple stresses.

A Healthy Soil for Healthy Yields

Roots and rhizosphere processes are vital for plant fitness and productivity and are key for helping to harness improvements in soil health. Plants have been bred for their high yield above-ground characteristics, but Dr Gaudin argues that this may have been at the expense of benefits to the root systems and the plants' ability to team up with soil microbes. Characteristics such as efficient foraging and uptake, which are beneficial in lower input environments, may have been lost.

Understanding how human selection has affected root traits and rhizosphere interactions can help inform breeding and management practices that promote natural resource acquisition. In 2016, Dr Gaudin was awarded a New Innovator in Food and Agricultural Research to address critical gaps in understanding how to optimise root systems that can better exploit improvements in soil health.

By analysing a wealth of data from maize crops bred over 10,000 years, Dr Gaudin's team is looking at how breeding has affected root characteristics, their associated microbes and their functional significance for resource cycling and acquisition when suboptimal.

'By testing how breeding has impacted corn and tomato root and rhizosphere processes critical to cycle and uptake resources, we hope to shed light on how breeders and producers can grow more productive and resilient crops and promote adoption of more sustainable practices at a large scale,' says Dr Gaudin.

Through their research and outreach activities, Dr Gaudin and her team are forging the way ahead for understanding ecological processes and applying these concepts to the management of farming systems. This comprehensive approach that builds sustainability promises to help develop more efficient and resilient cropping systems for the future.

Meet the researcher

Dr Amélie Gaudin
Department of Plant Sciences
University of California, Davis
Davis, CA
USA

Dr Amélie Gaudin completed her PhD in plant agriculture at the University of Guelph in 2011. Upon graduating, she worked as a postdoctoral researcher at the International Rice Research Institute and then the University of Guelph, before joining the faculty at the University of California, Davis (UC Davis) in 2015. She is currently Assistant Professor in the Department of Plant Sciences, where her team specialises in agroecology. Her research seeks to develop management strategies that emphasise soil health and biodiversity as a basis for improvement. Outreach activities and close collaboration with stakeholders ensures that her research is relevant to the sustainability of California's agriculture.

CONTACT

E: agaudin@ucdavis.edu
W: http://gaudin.ucdavis.edu

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REVITALISING PUERTO RICO TOWARDS SUSTAINABLE VEGETABLE PRODUCTION

Currently, farming practices in Puerto Rico are largely unsustainable and little information exists to direct growers towards better practice. To address this issue, **Dr Ermita Hernandez** and her team at the University of Puerto Rico investigate sustainable management practices, including using enhanced crop varieties and improving soil health through the use of organic amendments.

In a world where the population is booming, the climate is changing, and wilderness areas are diminishing, the pressure for high-yield agricultural production is on the rise. Intensification is occurring on a global scale, with the island of Puerto Rico being no exception.

To exacerbate these stresses, climate change has undermined the situation, disrupting rain and drought cycles, amongst other things. The resulting warmer temperatures, coupled with poor management practices, are thought to be responsible for an increased spread of pests and disease, as well as the emergence of new ones.

To make matters worse, there has been very little attention given to improving the crop varieties grown in Puerto Rico. Puerto Rican produce lacks resilience to rising temperatures, drought and disease, meaning that a single bad year could have a serious impact on the local agricultural economy.

Scant availability of information regarding best management practices has resulted in the increased dependence on agrochemicals (pesticides and fertilisers) to obtain high yields. Poor management can lead to the soil becoming depleted of essential nutrients for crop growth, leading to a further increased need for fertiliser application. Agrochemical production costs both financially and environmentally – an unsustainable option for the future of farming systems.

Puerto Rico's Tomato and Sweet Pepper Produce

Sweet peppers and tomatoes, both members of the *Solanaceae* family, are particularly important local produce in Puerto Rico. Together, their cropping range covers 47% of land dedicated to vegetable farming in Puerto Rico. The degree of sweet pepper farming is, however, experiencing rapid declines as yields have become unreliable and farmers simply can't take the risk.

Tomato production hasn't yet faired so badly, although these are grown in vast monocrop swathes. This lack of genetic diversity increases the susceptibility of plants to new stresses, including pests and disease, with potential for island-wide devastation if these threats were to emerge. Tomato production

therefore remains on a knife edge, and the situation is worsened by economical out-competition from overseas produce. The result involves mass tomato export, whilst 85% of vegetables consumed in Puerto Rico are imported from overseas, raising issues of food security.

Puerto Rico's position of strength as a large-scale *Solanaceae* producer is becoming jeopardised. Current farming practices are simply not sustainable – if future generations are to survive, a solution must be reached. Fortunately, Dr Ermita Hernandez from the University of Puerto Rico has stepped in to make a change. With the help of her extension and research colleagues, Dr Hernandez strives to discern the most sustainable, low-input management protocols for Puerto Rican tomato and sweet pepper production.

Her ambitions stretch beyond research however; by means of field days and demonstrations, Dr Hernandez provides guidance and information to local agronomists and farmers so that sustainable solutions can be put into practice.

Already having obtained funding for multiple projects, Dr Hernandez states that her work will explore the 'best sustainable management practices that can reduce high farming inputs and cost, while maintaining long-term soil and crop health for important vegetable production.'

Crop Compatibility and Species Improvement

One of Dr Hernandez's projects has involved the incorporation of cover crops into agricultural practices. Cover crops are planted on cultivated land to improve soil conditions. In this case, the researchers planted leguminous species due to their ability to reduce weed growth and increase the amount of organic matter in the soil.

Cover crops also lead to improved soil stability due to the presence of their roots. This reduces soil erosion in storms and heavy rainfall events, during which vital nutrients would otherwise be lost, rendering soils less fertile.

Dr Hernandez and her colleagues wanted to explore more than just cover crop compatibility. The team also evaluated the yields of different species of tomato and sweet pepper and assessed the outcome of applying rhizobacteria to the soils. Rhizobacteria comprise a diverse group of microbes that live in the roots of plants, or the 'rhizosphere'. They offer beneficial services to their host plant, including nutrient provision, disease resistance and can even control plant hormones to stimulate growth or defence mechanisms. These favours are provided in return for hospitable living conditions in the roots, critical for rhizobacterial survival.

Plots in Practice

The research team planted cover crops in several plots two months before tomatoes and sweet peppers were introduced, both on conventional and organic agricultural land, for comparison against plots where no

legumes were incorporated. The cover crops were applied in the form of a 'green manure', that could be easily used by farmers.

The team then created plots within these initial plots. Three different species of tomato (Skyway 687, BHN 602 and Dixie Red) and three types of sweet pepper (SPP9301, Key West and Grenada) were grown under three different conditions. These different conditions involved the addition of rhizobacteria species – *Bacillus subtilis, Bacillus amyloliquefaciens* and no rhizobacteria as a control.

Once the crops had been planted, treatments applied, and the growing season was in full swing, Dr Hernandez's team faced the challenge of monitoring pests, disease and yield on each of the plots. This laborious process involved measuring the quantity, weight and dimensions of the fruits present, as well as soil characteristics such as nutrient levels and organic matter content to indicate quality improvement.

The trial was run over a two-year period, providing the team with insight into potential strategies for better management of small-scale Puerto Rican farms. The incorporation of leguminous cover crops caused an 18% increase in the weight of sweet peppers grown in the first year, whilst the SPP9301 pepper variety significantly outcompeted Key West and Grenada in terms of yield during year two. Dr Hernandez and her colleagues hypothesised that applying *Bacillus amyloliquefaciens* may reduce the chance of bacterial leaf blight, improving agricultural resilience.

Conversion to Compost

An additional project, also headed by Dr Hernandez, looked specifically at the concern of Puerto Rican farmers' reliance on agrochemicals, including pesticides and fertilisers, in order to obtain high yields. Production and application of these chemicals comes at a huge expense not just financially, but also environmentally. Organic compost, as a nutrient source, is also thought to improve the structure of soils, increase the amount of water they can hold, and introduce beneficial organisms, compared with inorganic alternatives.

Whilst applying too little compost could reduce yields, too much can pose serious environmental risks. Important nutrients, including nitrogen and phosphorous, can easily be lost from soils during rain or erosion, ending up in local waterways. This sudden spike of nutrients can have severe impacts on aquatic ecology, often resulting in toxic algal blooms. With no information available on local crop requirements for organic compost as fertiliser, the team's first task was clear. They aimed to tackle this shortfall in geographically distinct regions throughout Puerto Rico.

Dr Hernandez and her colleagues coordinated several field experiments to figure out the organic compost requirements for the specific soil types and climates observed across Puerto Rico. They applied compost to soils and then prepared the fields based on commercial agronomic recommendations. To test the effectiveness of compost fertilisation, the team weighed fruits from the crops grown in these fields and compared the results with expected yields from non-organic fertiliser usage. They also conducted chemical soil analysis before planting and after harvest, to determine the amount of nutrients taken up by the crop species.

Outreach and Education

Dr Hernandez and her team have gone to great efforts to ensure effective communication of their strategies to the farming community. Webinars, as well as demonstration trials are put on for growers, designed to guide them through the processes of compost application, mulch and irrigation installation, seedling transplantation, monitoring and sampling. The benefits of using cover crops have also been communicated in the same way, both to organic and conventional growers, and the research team provides hands-on experience to help put their theory into context.

The team has also developed an online portal to facilitate discussion between growers, extension educators and other stakeholders. This is linked to social networking platforms, which are routinely maintained by Dr Hernandez, to ensure that relevant information is passed on and growers are kept up-to-date.

Future Directions

Dr Hernandez's work is ongoing, but this hasn't stopped her from keeping one eye on the future. She anticipates the creation of an Extension and Research Vegetable Program, to provide solutions and management strategies to growers throughout the vegetable industry. This will be complemented by a grower's handbook that describes 'the amount of compost needed for each vegetable crop and the best integrated crop management tactics in various geographical regions and growing periods in Puerto Rico.'

Meet the researcher

Dr Ermita Hernandez
Department of Agroenvironmental Science
College of Agricultural Sciences
University of Puerto Rico – Mayagüez Campus
Mayagüez
Puerto Rico

Dr Ermita Hernandez completed an associate degree in Horticulture at the University of Puerto Rico in 1999. Her early passion in the field, combined with her clear ability to inspire others, led her to pursue a degree in Agricultural Education thereafter she worked as an Agriculture Teacher at an elementary school at Puerto Rico. She went on to diversify her skills and knowledge with a Master's degree Plant Pathology at The Pennsylvania State University, swiftly followed by a Graduate Research and Teacher Assistant position at the same institution. Pennsylvania State University was clearly impressed with her tenacity in the field, offering Dr Hernandez a PhD position in Horticulture which she completed in 2013. She then returned to the University of Puerto Rico, where she was offered her current position of Assistant Professor/Vegetable Extension Specialist. Dr Hernandez's determination and commitment to the field is admirable, providing valuable contributions to current agroenvironmental research.

CONTACT

E: ermita.hernandez@upr.edu
W: http://www.ermitahernandez.com/
@empresadehortalizasuprm

KEY COLLABORATORS

Dr Bryan Brunner, University of Puerto Rico at Mayaguez
Isbeth Irizarry, Puerto Rico Agricultural Extension Service Agency
Moises Soto, Finca González
Kevin González, Finca González
Carlos González, Finca González
Francisco Arroyo, Finca KYV del Caribe
Derick Crespo Hernandez
Dr Joaquin Chong, University of Puerto Rico at Mayaguez

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TOWARDS SUSTAINABLE YAM PRODUCTION IN PUERTO RICO

Yams provide a staple food source in Puerto Rico, supplying an essential source of nutrients and fibre. However, pests and disease have been severely diminishing local yields. To tackle this problem, **Dr Merari Feliciano-Rivera** and her team at the University of Puerto Rico are working to characterise the causal agents, provide management techniques and improve seed production practices towards sustainable yam production.

In the 80s, yam was considered the most important root crop in Puerto Rico and was highly profitable for farmers. Since then, the industry has been declining due to several factors, including foliar and tuber diseases, cheap imports, natural disasters and high production costs. Yam production decreased by two and a half times over just a thirty-year period.

Yams are considered a staple food in tropical and subtropical regions, following only potatoes and cassava as the most important starchy root crop worldwide. They provide a rich source of vitamin C, potassium, manganese and fibre and are low in cholesterol. In Puerto Rico, the most cultivated yams species include *Dioscorea alata* and *Dioscorea rotundata.*

Yam seeds are scarce and expensive, especially when sourcing a good quality crop. The plant is also affected by many pests and diseases, including soil pests such as white worm and nematodes – the main drivers of yam decimation in Puerto Rico. No nematicides are registered for use on tubers; dry rot takes over, severely diminishing harvests. Nematodes belonging to the *Pratylenchus* and *Scutellonema* families are the main causal agents in Puerto Rico.

Dioscorea rotundata is particularly susceptible to *internal* dry rot, which causes its tubers to harden, dry out and decay during storage, allowing subsequent invasion by a plethora of fungal species. *Internal* dry rot differs from dry rot in that it is caused by fungi rather than nematodes, and affects yams during storage, rather than both in the field and through storage. This disease has direct impacts on seed quality and causes yield losses of up to 98%. Across the globe, *internal* dry rot has been reported to be caused by infestations of *Penicillium*, *Fusarium* and *Rhizoctonia* fungi.

To determine preventative measures, identifying the most dominant local effector is vital. The application of fungicides before storage and planting has previously been proven to improve yam quality. 'Oxamyl L' used to be the go-to dry rot diminisher, however, this product is no longer registered for use on tubers in Puerto Rico, and is currently only registered for foliar application.

Both popular yam species are also prone to a disease called yam anthracnose, and yield losses of up to 90% have been observed as a result of this fungal infection in *Dioscorea alata* yams. Anthracnose causes black lesions on yam foliage, resulting in the premature loss of leafy material. As the plant depends on its chlorophyll-containing foliage to provide energy for growth, leaf loss has a serious impact on the size of the resultant tubers. Globally, anthracnose is caused by the *Colletotrichum gloesporioides* fungus; however, the species occurring in Puerto Rico was, until recently, unknown. As anthracnose spreads, traditional

agricultural techniques, including intercropping and field rotation, have had minimal impacts. As anthracnose spores are often blown from distant fields, it is near impossible to quarantine the crop from the cause. In the case of dry rot, although these agricultural techniques have been advised and are appropriate in theory, certain factors again make mitigation a challenge. The small scale of many Puerto Rican plots, which leads to diseased and healthy fields being in close proximity, means that such disease control precautions are often inadequate.

While Puerto Rican farmers despair at their diminishing produce, Dr Merari Feliciano-Rivera and her colleagues at the University of Puerto Rico are working to reverse the trend. 'Our research focus is to reduce postharvest losses and improve product quality,' Dr Feliciano-Rivera states. 'We also aim to develop effective management tools and accurate strategies for diseases, identify and describe the causal agents using molecular tools, and evaluate propagation techniques to increase seed production.' Although this may seem ambitious, Dr Feliciano-Rivera and her colleagues have undergone serious endeavours to provide farmers with new techniques of yielding yam.

Internal Dry Rot

In order to tackle *internal* dry rot proliferation in Puerto Rico, which currently affects stored yam tubers, Dr Feliciano-Rivera and her graduate student Casiani Soto Ramos endeavoured to identify and characterise the infectious fungal species. They collected ten symptomatic tubers and analysed them at the Plant Pathology and Epidemiology Laboratory, AES Isabela. Here, the team classified 47 different fungal isolates: 32 of Penicillium, seven *Aspergillus*, five *Fusarium* and three *Botryoshpaeracea*. They characterised each fungal species and analysed their disease-causing potential. The team's findings suggested that multiple Penicillium species drive *internal* dry rot of Dioscorea rotundata yams in Puerto Rico, providing a tangible target for mitigation initiatives.

Once identified, Dr Feliciano-Rivera and her colleagues aimed to test the effectiveness of different pesticides to control *internal* dry rot disease. The team first dipped cut diseased tubers into one of a variety of pesticides. They applied each individual treatment four times to 25 tubers, assessing each yam at 15-day intervals throughout storage. After cutting tubers into seed-pieces and re-applying the same set of treatments, the team planted the treated yam seeds in the field, and conducted monthly assessments for signs of disease. They also analysed the soils in which each tuber grew and measured tuber weight to determine yield.

Improving Seed Production

Further work by Dr Feliciano-Rivera and her colleagues has involved assessing yam spacing in agricultural fields and applying a method known as the 'minisett technique' to improve seed production.

They conducted field trials with Dioscorea rotundata yams, to assess the effectiveness of the minisett technique to improve seed production. The minisett technique involves cutting a parent yam tuber into pieces – minisetts – smaller than those traditionally used for seed production (20–50 g rather than 200–250 g).

Before planting, the team treats these minisetts with pesticides to prevent diseases. They then plant the pieces in small nursery beds for one month, before transplanting them into the field for further evaluations. In their current fields trials, Dr Feliciano-Rivera and her team are evaluating the combination of three sizes and three planting distances.

This method provides more rapid in-field crop establishment. It also means that fewer tubers are required for seeding, allowing more to be sold or consumed, and reducing overall costs.

Defeating Dry Rot

The researchers also aimed to identify whether nematicide treatments could reduce dry rot. They used untreated tubers as a control, and treated others with different combinations of pesticides: Vydate L®, Sesamin EC® and Nemakill®. The application methods were varied: through irrigation, and direct foliar application.

Dr Feliciano-Rivera's team assessed nematode populations in the soil and tubers three times throughout the crop cycle and determined that none of their proposed treatments were effective in controlling the *Pratylenchus coffeae* nematode, highlighting the urgency for further research into an effective dry rot treatment.

Reducing Anthracnose

Dr Feliciano-Rivera and her team did not stop at dry rot – they extended their efforts to understand and reduce yam anthracnose. To determine just how detrimental the disease had been throughout Puerto Rico, and to characterise the causal species of *Colletotrichum* fungus locally, the team collected 224 fungal samples from infected yam crops located around the island.

They examined the different fungal species and their disease-causing potential and found that *Colletotrichum gloesporioides* comprises one of nine species that appear on *Dioscorea alata* yams, with a further five presenting otherwise unreported local pathogenic strains. The researchers confirmed that *Colletotrichum* fungus found on both *Dioscorea alata* and Dioscorea rotundata yams is pathogenic and causes anthracnose in both cases. Of the entire island, they found that the town of Barranquitas experienced the most significant impacts, reporting 60% disease severity here.

Dr Feliciano-Rivera's team then went on to assess a range of organic and conventional fungicides, to determine whether any could effectively control anthracnose. Dr Feliciano-Rivera and her graduate student Yara Rosada performed *in vitro* and *in vivo* tests, to find promising fungicides for managing foliar diseases of yam including anthracnose. They assessed the state of foliage for the absence of anthracnose-induced lesions and scars. Their findings suggest that plant-based extracts have no positive effect reducing yam anthracnose. A fungicide composed of Cyprodinil and Fludioxonil was the most effective fungicide for managing anthracnose in the field and producing the highest yields. This agreed with the team's in vitro analysis, where this fungicide was one of three treatments identified to inhibit *Calletotrichum* growth.

Future Work

Dr Feliciano-Rivera's research has come a long way to better yield the yam, but more is in the pipeline. The researchers aim to improve yam propagation rates, 'to maximise the production of disease-free propagation material for the farmers', using Temporary Immersion Bioreactor technologies.

Tissue culture is a common method used to produce multiple discrete plantlets from a single parent plant, through growth of parent tissue on nutrient media. Conventional methods are limited due to high labour requirements, low multiplication rates and long multiplication periods. Through the use of liquid media flowing between separate tissue-containing vessels, in which the gaseous exchange, nutrient uptake and illumination are controlled by an automated system, the 'Temporary Immersion Bioreactor' method avoids these drawbacks. This system therefore provides an affordable, speedy means of achieving higher quality plantlet production.

Dr Feliciano-Rivera's team aims to establish a best practise Temporary Immersion Bioreactor protocol for large-scale yam and arracacha propagation. Once in place, they will implement quality control using molecular markers to flag up tubers with low genetic fidelity. In time, this will provide certification to confirm propagation material quality, ultimately improving yield and reducing costs for Puerto Rican farmers.

The team's next steps also involve developing an integrated pest management program and production guide to provide users with an easily understandable overview of the results of their research. The guide is anticipated to be split into two sections of recommendations: general production, followed by disease control. The information itself will be targeted at Puerto Rican farmers, with specific recommendations for the area.

The researchers also plan to, 'complete the third year of field evaluation of the minisett techniques to increase the production of yam seed'. Progress has so far been positive, providing a more certain future for yam farmers in Puerto Rico.

Meet the researcher

Dr Merari Feliciano-Rivera
Department of Agro-Environmental Sciences
University of Puerto Rico, Mayagüez Campus
Mayagüez
Puerto Rico

After completing her BSc in Agricultural Education at the University of Puerto Rico, Dr Merari Feliciano-Rivera extended her term here, completing her MSc in Crop Protection in 2007, followed by a PhD in Plant Pathology in 2011. Upon completing her PhD, Dr Feliciano-Rivera was then appointed the role of Assistant Professor at the University of Puerto Rico, Mayagüez Campus. Here, she was promoted to her current role as Associate Professor in 2015. For her outstanding research in plant pathology, Dr Feliciano-Rivera has received a number of honours, awards, achievements and several USDA funded grants. She has acted as a reviewer of scientific journals, been invited to speak at numerous conferences and seminars, and produced an extensive list of published papers. As well as undertaking research, she advises a number of graduate and undergraduate students, and teaches several graduate courses, including Advanced Plant Pathology, Research Methods in Plant Pathology and Disease Epidemiology.

CONTACT

E: merari.feliciano@upr.edu

KEY COLLABORATORS

Jesús M Cardona – Research Associate, Agricultural Experiment Station of Isabela, PR Department of Agro-environmental Science, University of Puerto Rico, Mayagüez Campus
Agenol González – Professor, Agricultural Experiment Station of Corozal, PR, Department of Agro-environmental Science, University of Puerto Rico, Mayagüez Campus
Lydia Rivera Vargas – Professor, Department of Agro-environmental Science, University of Puerto Rico, Mayagüez Campus
Stephanie Fuentes – Graduate Student, Department of Agro-environmental Science, University of Puerto Rico, Mayagüez Campus
Casiani Soto – Graduate Student, Department of Agro-environmental Science, University of Puerto Rico, Mayagüez Campus
Yanira Miranda – Graduate Student, Department of Agro-environmental Science, University of Puerto Rico, Mayagüez Campus
Seylie Serrano – Graduate Student, Department of Agro-environmental Science, University of Puerto Rico, Mayagüez Campus
Yaniel Roman – Graduate Student, Department of Agro-environmental Science, University of Puerto Rico, Mayagüez Campus
Yara Rosado – Graduate Student, Department of Agro-environmental Science, University of Puerto Rico, Mayagüez Campus
Jose A. Chavarria – Professor, Department of Agro-environmental Science, University of Puerto Rico, Mayagüez Campus

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FROM FOES TO FRIENDS: EXPLOITING THE AGRICULTURAL POTENTIAL OF WEEDS

Dr Te-Ming Paul Tseng and his research group at Mississippi State University are investigating the biology and ecology of agricultural weeds to limit their damage to crops. The team also hopes to improve crop productivity by incorporating competitive traits from weeds into crops.

Agricultural weeds are a major threat to global agriculture. Weeds divert water, soil nutrients and sunlight away from crops, and often host insect pests and pathogens that are harmful to crops. Weeds can also overwhelm crop plants through 'allelopathy' – releasing chemicals that inhibit crop growth. Many weeds thrive in warmer climates, and it's predicted that climate change will reduce global agricultural productivity by 10–20%, posing a challenge to global food security.

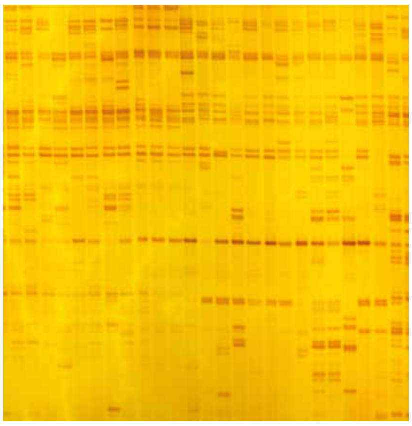
So, what can be done to reduce the impact of weeds on our crop production? Hoping to answer this pertinent question is Dr Te-Ming Paul Tseng at Mississippi State University. Dr Tseng and his team are investigating the physiology and ecology of weeds, their interactions with crops, and how to combat weed damage. They are even exploring ways to repurpose weeds for agriculturally good purposes!

The team conducts field studies, plant breeding, biological analysis, and increasingly, they are probing into plant DNA with cutting-edge genomics tools. Their Mississippi research facility is located in the heart of America's Southern Rice Belt, and incidentally, their major research focus is rice. However, their research scope extends beyond rice and covers weeds that affect other important crops, such as tomatoes, sweet potato and soybean.

Turning Feral: The Evolution of Weedy Rice

The Japanese proverb, 'A meal without rice is no meal', rings true across the world. Rice is the world's second most popular staple crop (after wheat), with over 150 million hectares cultivated worldwide. In the US, rice agriculture is centred in two main regions: the Rice Belt (Southern Mississippi River Delta), spanning the Southern states of Arkansas, Louisiana, Mississippi, Missouri, and Texas, and also California's Sacramento valley.

Cultivated rice, *Oryza sativa*, is thought to have been domesticated from wild rice, *Oryza rufipogon*, in China about 8000–13000 years ago, leading to three distinct *Oryza sativa* varieties grown today – indica, *japonica*, and javanica. Cultivated rice can also become 'de-domesticated' – reverting back to a feral or wild state known as 'weedy rice'. Weedy rice has a pervasive presence in rice paddy fields across the world, sometimes leading to yield losses of 80%.



Weedy rice has nifty adaptations that gives it the edge over cultivated rice – variable emergence, a high degree of seed dispersal, diversity in seed dormancy times, and seed longevity in soil. These weedy traits are the result of the evolution of genes that enable adaptability to harsh agricultural ecosystems. Indeed, rice will become progressively weed-like if this natural selection is allowed to play out.

Various weedy rice varieties have emerged in rice-growing regions worldwide, and these exhibit considerable genetic variation. Cross-breeding with agricultural rice and even closely-related wild rice varieties also plays a role in the evolution of weedy rice. It is thought that agricultural practices and agricultural ecology are major factors in this process, and Dr Tseng's group are investigating this. While it's not possible to go back in time, the team are able to track the progression of weedy crop de-domestication process by looking at DNA and physiology. The group has done this for weedy rice varieties, using a combination of rice husbandry, DNA sequencing ('genotyping') and investigating observable traits ('phenotyping').

Weedy rice is a huge problem in America's two rice regions. The varieties found in the southern states and California represent weedy rice at different stages in its evolution, reflecting the differences in their respective histories and agricultural practices. There is no native wild rice in America, so these varieties have descended entirely from historically cultivated varieties. Comparing weedy rice varieties found in Arkansas (a southern state) with those found in California presents unmissable study opportunities. By probing the relationships between genes and observable traits using DNA sequencing, Dr Tseng and his team have obtained 'snapshots in time' of weedy rice evolution.

Rice cultivation was introduced to the South in the late 17th century, whereas the Californian rice industry was established more recently in the early 20th century. Unsurprisingly, the group's DNA analyses found that the Californian weedy rice ecotype is very early in its evolution – only 118 generations (not long in rice years!) since it diverged from the *japonica* variety commonly cultivated in California. At this early phase in its de-domestication, it has little genetic diversity and phenotypes (collections of observable traits) that are almost identical to cultivated *japonica* rice – straw hull colour, poor seed dispersal, similar maturity dates, and similar grain characteristics. The group speculates that 'mimicry' of cultivated rice is what allows it to spread so easily. As 'good' and 'weedy' rice varieties are virtually indistinguishable, farmers may be inadvertently harvesting and breeding the weed, thinking it's the crop.

In contrast, the group found that Arkansan weedy rice – descended from 17th century rice cultivars – exhibited greater genetic and phenotypic diversity, with more weed-like traits. These observations suggest that that they are further along in their de-domestication, and have diversified to fill various ecological niches within the agricultural ecosystems of Arkansas. Moreover, two phenotypes – strawhull and blackhull – were associated with prevailing agricultural practices. Tillage is a common agricultural practice, though inadvertently spreads weedy rice seeds. Strawhull weeds were associated with fields that underwent tillage or rotation between soybean and rice. In no-till fields, the more aggressive blackhull weeds were prevalent, with later maturity, easy seed dispersal and longer stems – necessary to ensure seed dissemination without human intervention!

Historically, herbicides were not an option for controlling weedy rice, as they would also affect the crop, both being the same species. Chemicals known as imidazolinones, such as imazethapyr, are toxic to weedy rice and could be an effective herbicide, but how can farmers avoid collateral damage to the crop? Clearfield® is a rice variety bred to be herbicide-resistant, and can be used with imidazolinone to clear

away the weeds. After being commercialised in 2002, for the Southern Rice Belt, Clearfield® technology has been reportedly successful – in the US and beyond. In Arkansas, it's estimated that about 60% of the rice acreage is Clearfield®.

However, there is the potential for Clearfield® to cross-breed with weedy rice, leading to a transfer of herbicide-resistance genes to weeds. Fortunately, a number of biological factors will reduce – but not eliminate – this risk. For example, in the Southern Rice Belt, the *japonica* cultivar is only very distantly related the strawhull and blackhull weedy rice populations, reducing the chance of them producing viable fertile offspring. However, herbicide-resistant weedy outcrosses have still been reported worldwide. Dr Tseng and his team have investigated weedy rice herbicide-resistance in Arkansas Clearfield® rice fields. They discovered that 10–60% of crop-weed hybrids were herbicide resistant, and hybridisation is driving the evolution of new traits not seen in historic weedy rice populations. Moreover, herbicide-resistant hybrids were observed to have fewer weedy traits.

Weedy Rice as a Source of Competitive Traits

Selective breeding has become 'smarter' with modern tools such as gene sequencing, and is instrumental in improving crop traits. However, a major downside of selective breeding is the loss of genetic diversity. Modern rice varieties are composed of almost identical individual plants, meaning that they may be ill-adapted to changing environmental conditions – such as new pests, diseases and climate change. Sadly, many 'heritage' varieties are falling into disuse, and wild rice populations are facing possible extinction – representing a loss of invaluable agricultural genetic resources.

Dr Tseng's group is investigating weedy rice varieties as an alternative untapped resource – a diverse source of traits that could improve agricultural rice's adaptability breeding programmes or genetic engineering strategies. Moreover, they may have inherited their hardy traits from wild rice and extinct cultivars, representing a treasure trove of long-forgotten varieties. The team is investigating weedy rice tolerance to environmental conditions, including cold temperatures and soil-depth. They are also investigating how weedy rice releases chemicals that inhibit crop growth, with the view of incorporating this into crop rice, as a means of suppressing competition.

Deer Repellent from Sicklepods

Soybean is an important leguminous food crop, as a source of protein in animal feed, and meat- and dairy-substitutes. As well as vegans and livestock, wild deer are very fond of soybean! Deer can cause great damage to soybean crops, and cause up to 80% loss in yields. Current deer-proof interventions have limitations – fencing is expensive, and repellents lose effectiveness after rainfall.

Dr Tseng and his team found that sicklepod – a particularly troublesome weed to US soybean – contains high quantities of chemicals called anthraquinones, which may be the most effective anti-herbivory strategy of any plant, against both insects and mammals – including deer. In field tests at Mississippi State University's Captive Deer Facility, the team demonstrated that extracted anthraquinones repelled deer away from the soybean crop. Moreover, they determined that sicklepod roots contained the highest concentrations, and may be used as a natural deer repellent. Soybeans also produce anthraquinones, albeit 11-fold less than sicklepod. As a future work, the research team hopes to carry out breeding strategies to develop soybean varieties that produce high levels of anthraquinone.

Summary

Reducing weed competition with crops is a major priority for global agriculture. Dr Tseng's group is systematically investigating weed biology using cutting-edge tools. They have demonstrated how agricultural interventions can inadvertently drive weed evolution – in the case of weedy rice. Weeds have incredible genetic diversity, having escaped the 'genetic bottleneck' faced by many crop varieties, and thus possess remarkable adaptations to harsh agricultural environments. As the group has demonstrated with weedy rice and sicklepod, these traits may be exploited by crops to improve agricultural productivity. Perhaps then, we should think of weeds not as nuisances, but as valuable resources!

Meet the researcher

Dr Te-Ming Paul Tseng
Department of Plant and Soil Sciences
Mississippi State University
Mississippi State, MS
USA

Dr Te-Ming Paul Tseng earned a PhD in Cell and Molecular Biology in Weed Science from University of Arkansas, Fayetteville in 2013. Upon graduating, he worked as a postdoctoral research associate in weed physiology at University of Arkansas, followed by a postdoctoral research associate in plant pathology at Purdue University. Since 2015, Dr Tseng has been an Assistant Professor of Weed Physiology in the Department of Plant and Soil Sciences at Mississippi State University (MSU). His team studies the biology, ecology, and physiology of weeds, with the ultimate goal of improving weed management practices. His current research projects focus on the evolution, physiology and molecular mechanisms of herbicide resistance in weeds, and characterising the genetic basis of competitive traits in weeds. In addition to his research, Dr Tseng teaches the Herbicide Physiology & Biochemistry, Environmental Fate of Herbicides, and Weed Ecology & Biology undergraduate modules, and seeks to cultivate the next generation of molecular plant breeding researchers. He is also active in outreach to stakeholders in agriculture, industry and public policy.

CONTACT

E: t.tseng@msstate.edu
W: http://www.pss.msstate.edu/associate.asp?id=163

MISSISSIPPI STATE UNIVERSITY

KEY COLLABORATORS

Rick Snyder, MSU
Casey Barickman, MSU
Steve Meyer, MSU
Marcus Lashley, MSU
Jay McCurdy, MSU
Amelia Fox, MSU
Nilda Burgos, University of Arkansas
Amy Lawton-Rauh, Clemson University
Sukumar Saha, USDA ARS
Vijay Nandula, USDA ARS

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SUB-ZERO SURVIVAL: REVEALING HOW PLANTS FREEZE

Watching plants return to life after a spell of cold winter weather can seem like a miracle. For over a century, biologists have understood that plant survival depends on a variety of co-dependent mechanisms, yet their methods for coping with temperatures far below freezing are still poorly understood. **Dr David Livingston** and **Dr Michael Wisniewski** of the US Department of Agriculture have provided fresh insights into these mechanisms, with the help of remarkably intricate imaging techniques.

In temperate climates, many actively growing plants are not adapted to long periods of freezing weather, and will typically die if they freeze or remain frozen for too long. This isn't always the case though – over centuries, farmers have gained a deep knowledge of which crops they are able to plant over the winter. Grains such as wheat, and root vegetables, are ideal candidates, and have ensured the survival of many civilizations over harsh winters.

However, as the Earth's climate changes, the ability of plants to adapt is becoming more complicated. Increasingly frequent weather extremes mean that periods of warmer weather, particularly in late winter and early spring, are increasingly interspersed with harsh cold snaps, pushing the coping mechanisms of winter crops to extremes – a cause for concern for farmers.

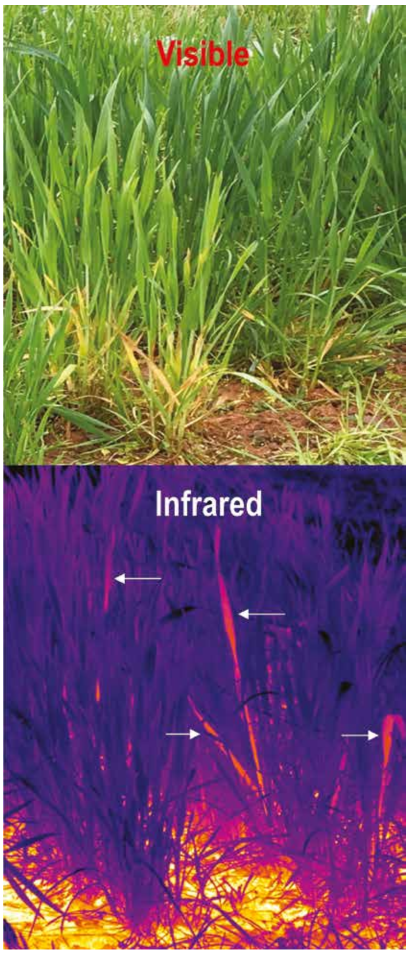
One solution to this problem could lie in the breeding of better adapted varieties. Studies have revealed that different varieties of crops resist freezing in different ways. While some may ensure their seeds remain alive over winter, others will see their leaves and shoots coming back strong after being frozen. Yet in order to breed crops with multiple mechanisms for tolerating freezes, a detailed knowledge of the freezing process in plants is needed.

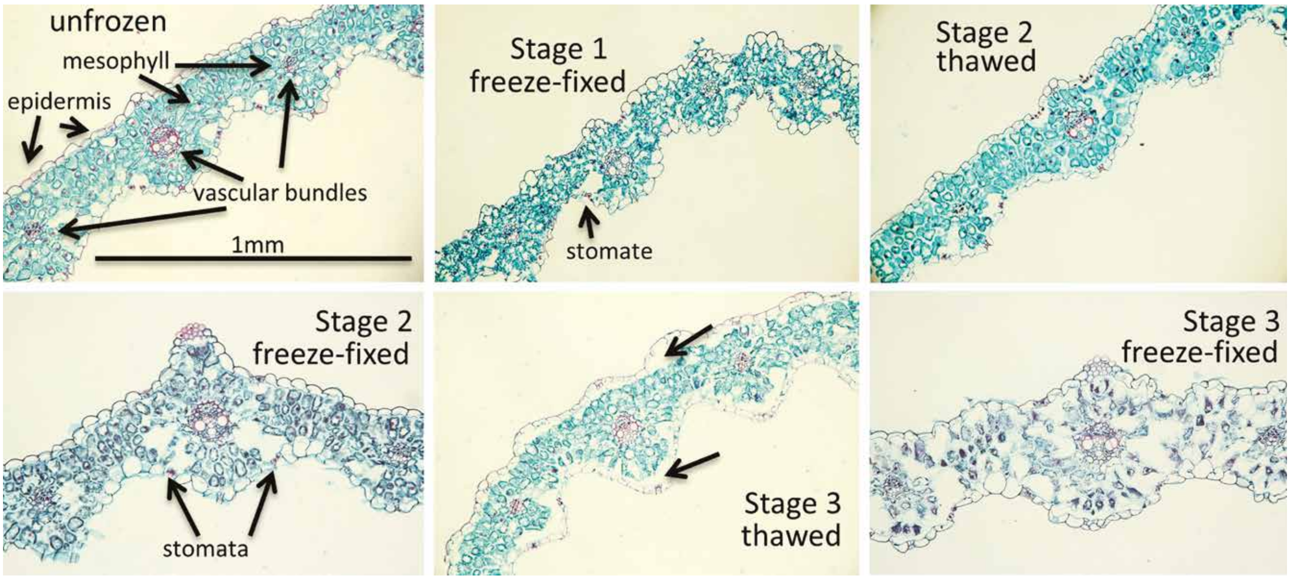
In their recent research, Dr David Livingston and Dr Michael Wisniewski of the US Department of Agriculture – Agricultural Research Service have focused on gaining an in-depth understanding of how different plants and crop varieties resist freezing. They hope that this information will allow breeders to select new varieties that can more readily tolerate extremes in climate.

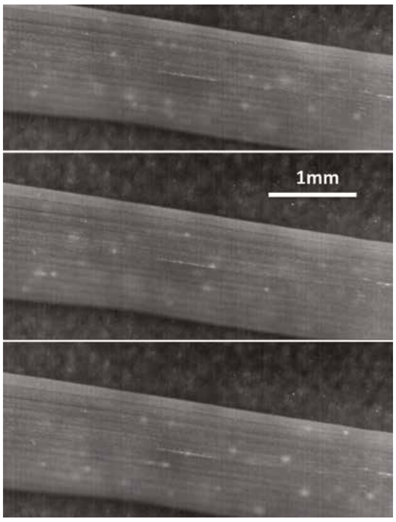
Intricate Infra-Red Images

In 2015, Drs Livingston and Wisniewski, along with other colleagues, used a high-resolution infrared (IR) camera to precisely document the overnight freezing processes that occur in crops during a frost event. By measuring subtle changes in heat emitted by the plants, the camera enabled them to gain greater insights into freezing processes under natural conditions than had previously been achieved.

'The high-definition IR camera was able to resolve freezing in individual cells, which allowed us to generate a series of videos that will potentially correct many misconceptions that may have hampered the progress of improving







Close up of a wheat leaf at -5°C, showing individual cells freezing as small fuzzy white dots scattered around the leaf. When viewed in real time, this freeze event resembles firefly activity.

freezing tolerance in crop plants,' Dr Livingston explains. 'The quality of the infrared recordings obtained in this study is unprecedented.'

In a laboratory study, the IR camera was used to create a series of videos of winter wheat under controlled conditions, subjected to temperatures as low as −18°C. In 2017, the laboratory studies led Dr Livingston and Dr Wisniewski to monitor wheat plants under a natural frost event in which the temperatures dropped to about −8°C. In both experiments, the videos revealed a wide range of freezing phenomena that had never been observed previously.

Thanks to the use of this technology, biologists now have a more in-depth understanding of the freezing responses that occur in plants under laboratory and natural conditions.

Resistance to Freezing

One of the most fascinating phenomena demonstrated by Dr Wisniewski, Dr Livingston and their colleagues was the ability of certain parts of wheat, and indeed entire plants, to avoid freezing at sub-zero temperatures. This process is called supercooling and allows plants to avoid freezing injury.

'During winter, if water freezes inside plants, severe damage to individual tissues can result,' says Dr Livingston. 'Infrared analysis indicates that while most of the plant may freeze, other parts of the plant simply supercool, meaning the water goes below the freezing point but does not actually freeze. Plants have the ability to supercool in different tissues and survive winter temperatures even though freezing may kill other parts of the plant. This is why your lawn may turn brown in the winter but come back like new in the spring.'

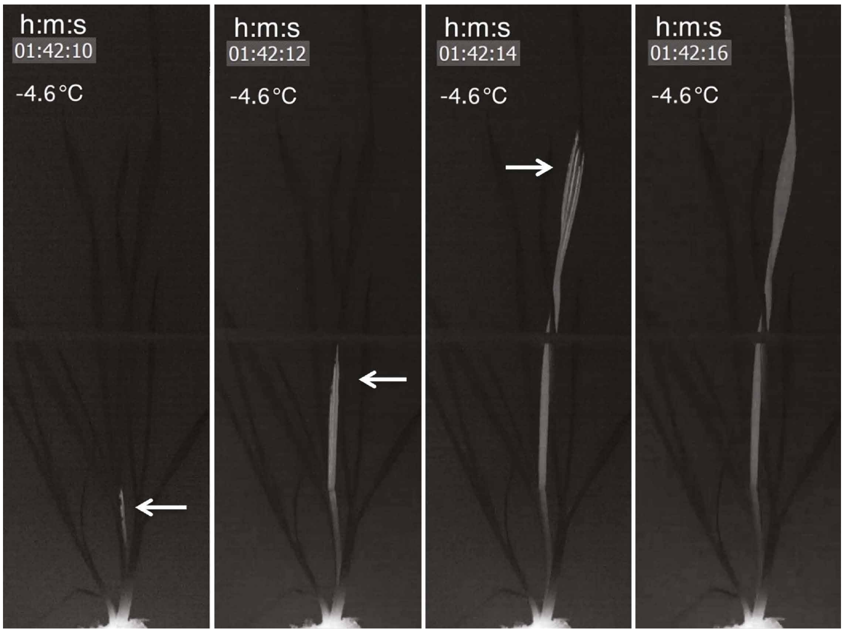
Drs Wisniewski and Livingston realised that supercooling plays an important role in winter survival, and emphasise how an advanced understanding of supercooling could greatly assist in the breeding of winter hardy crops. For example, some crop species will survive winter by supercooling, while others will tolerate freezing and survive winter temperatures quite easily, as long as the temperatures don't drop too low or stay low for an extended period of time.

'The goal of our program is to identify the mechanisms used by plants to survive freezing so that breeders can incorporate those mechanisms in existing crops and improve their tolerance to freezing temperatures,' Dr Livingston explains. But as the researchers discovered, genetics is not the only factor that determines freezing responses.

Unpredictable Freezing Patterns

By taking the first high-resolution videos of crops freezing under natural conditions, the team's research inevitably led to observations that contradicted previous ideas about freezing patterns. For example, they observed that the order in which individual plants freeze within a group of plants of the same crop is far less predictable than biologists had believed. Dr Wisniewski and Dr Livingston propose that heat rising up from the soil had an effect on the unpredictable order of freezing.

'Considerable heat flow from the soil was observed during freezing, which created turbulence in the temperatures



A single leaf freezing on a wheat plant. Note that freezing begins at the bottom of the plant and progresses to the top. Plants in the laboratory and in the field always froze from the bottom up even though the tops of the leaves were always colder than the bottom.

within the plant canopy,' Dr Livingston recalls. 'Rather than all plants freezing at a similar temperature, plants froze one at a time throughout the night, beginning shortly after air temperatures fell below 0°C and lasting until just before sunrise when temperatures had reached as low as −8°C.'

The biologists were not limited to observing plants as a whole – using their IR camera they also managed to reveal the order in which individual leaves undergo freezing. As Dr Livingston explains, 'leaves on each plant also froze one at a time. Interestingly, older leaves, that froze first, had a significantly higher percentage of water than younger leaves.'

In greater detail still, the images revealed the progression of freezing throughout individual plants. 'Freezing always began at the base of the plant and progressed to the top, even though the tops of plants were colder than the base,' adds Dr Livingston.

Three Stages of Freezing

An additional important aspect of winter survival revealed by the IR camera was that the process of freezing itself does not necessarily kill plant tissue. In reality, the situation is more complex because freezing takes place in three distinct stages.

'The first stage of freezing in wheat is propagated in vascular bundles of leaves,' says Dr Livingston. After this initial freezing, the IR-images clearly show how the freezing process spreads through the rest of the tissue as it cools further. 'Neither of the first two stages of freezing is lethal in some wheat leaves, but, a third stage of freezing is lethal, and is likely the result of dehydration stress. While stage one and two are sudden, non-equilibrium freezes that are observable using IR technology, stage three is a slow, equilibrium freeze that is not detectable by infrared thermography.'

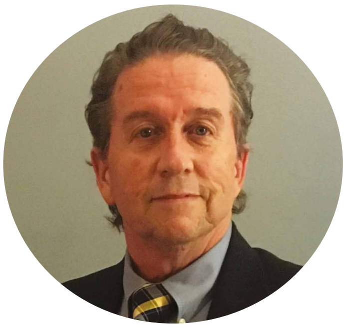
So ultimately, in some tissues freezing itself is not a death sentence, as long as it does not progress to the third stage. 'Microscopic observation suggests that death from stage three freezing is a result of the separation of the outer layer of cells from inner tissue cells after thawing and not from rupture of cells during freezing,' explains Dr Livingston. If the plant manages to thaw out before this level of damage occurs, the plant will have a good chance of surviving and recovering. This insight could be vitally important for breeders wishing to develop freezing-resistant crops through selection.

Adapting to a Changing Climate

As the Earth's climate becomes increasingly unpredictable, Dr Livingston, Dr Wisniewski, and their colleagues believe their work will be vital to understanding how agricultural practices will need to adapt to more frequent weather extremes.

'If, as expected, temperatures during winter and spring become more and more erratic, resulting in temperature extremes at unpredictable times, it will be essential to have a correct understanding of how freezing begins and propagates in plants so that logical approaches to improving freezing tolerance can be developed,' says Dr Livingston.

In the future, the researchers hope to investigate freezing patterns at a deeper level, enabling them to identify genetic traits that can be used to select and develop high-yielding, freezing-tolerant crops. 'We want to discover why grain crops freeze from the bottom up instead of the top down, as has always been assumed. We also want to know the reason older leaves of crops freeze first at a warmer sub-zero temperature and why the youngest leaves only freeze at extremely low temperatures,' Dr Livingston concludes. 'It is expected that these and other mechanisms used by plants to survive freezing can be transferred into less freezing tolerant but higher yielding varieties allowing the cultivation of normally winter tender grain crops such as oats in colder climates.'



Meet the researchers

Dr David Livingston
Plant Science Research
United States Department of Agriculture
Raleigh, NC
USA

Dr David Livingston works as a USDA Research Agronomist and Professor at North Carolina State University investigating the physiology of freezing tolerance in grain crops. He obtained his PhD at Michigan State University and worked for the USDA at Penn State University as an oat and barley breeder with a focus on improving freezing tolerance. He was transferred to Raleigh North Carolina in 1994, focusing on tolerance of wheat to spring freeze events using infrared thermography. Dr Livingston is now working with collaborators to combine infrared observations and 3D reconstruction, helping breeders to select individual freezing tolerant plants more effectively.

CONTACT

E: David.Livingston@ars.usda.gov
W: ars.usda.gov/people-locations/person?person-id=3402

Dr Michael Wisniewski
Innovative Fruit Production, Improvement and Protection
United States Department of Agriculture
Kearneysville, WV
USA

Dr Michael Wisniewski completed his PhD in Botany and Plant Pathology at the University of New Hampshire in 1983, before becoming a Research Plant Physiologist at the USDA's Appalachian Fruit Research Station. He is now the Supervisory Lead Scientist at the station, where his research interests include the stress physiology of fruit trees, cold hardiness and frost protection, and biological control of postharvest diseases. As well as being awarded several patents for his agricultural innovations, Dr Wisniewski has achieved many awards for his research, including the American Horticultural Society's Outstanding Researcher Award in 2011.

CONTACT

E: michael.wisniewski@ars.usda.gov
W: ars.usda.gov/northeast-area/kearneysville-wv/appalachian-fruit-research-laboratory/innovative-fruit-production-improvement-and-protection/people/michael-wisniewski/

KEY COLLABORATORS

Tan Duy Tuong, Plant Science Research, USDA
J Paul Murphy, Small Grains Breeding, North Carolina State University

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MORE REASONS TO EAT YOUR GREENS: BOOSTING PHYTOCHEMICALS IN VEGETABLES

Many plants contain phytochemicals – unique chemicals that can prevent diseases such as heart disease, cancer and obesity. **Dr C. B. Rajashekar** and his colleagues at Kansas State University are investigating ways to increase the concentration of these constituents in common vegetables, without adversely affecting normal growth and yield. The key lies in subjecting them to mild environmental stresses.

Increasing the Concentration of Phytochemicals in Common Vegetables

Phytochemicals are a large group of biologically active agents found in plants. Often, they have a therapeutic capacity, working as anticarcinogenics, antimutagenics, anti-inflammatory agents, and antioxidants. Therefore, they are associated with numerous health benefits. Phytochemicals play an important role in prevention of many chronic diseases such as heart disease, cancer and obesity. Common fruits and vegetables are often quite rich in phytochemicals. As such, many health organisations and doctors recommend that fruits and vegetables should be a major component of people's daily diet.

Because of the inherent health benefits of fruits and vegetables, many scientists have been attempting to improve their nutritional quality further. One approach is to stimulate enhanced production of health-promoting phytochemicals within the plant. Dr C. B. Rajashekar, Professor of Food Crops and Phytochemicals at Kansas State University's Department of Horticulture is investigating the use of certain environmental and crop management techniques to do exactly that – without damaging the overall quality, yield and growth characteristics. Specifically, his team investigates the ability of mild environmental stresses to encourage phytochemical production.

His approach exploits the natural response of many living organisms to stress. 'In response to stresses, and more importantly, as an adaptive mechanism, plants tend to shift toward secondary metabolism resulting in the accumulation of protective antioxidants,' explained Dr Rajashekar and his colleagues in a paper of 2009. Their research essentially involves the manipulation of this effect, as applied to commonly consumed vegetables such as lettuce, spinach, pac-choi and tomato and sprouts. Dr Rajashekar aims to use this information to improve the quality of produce and farming practices which will, in turn, lead to better health outcomes for global citizens.

Stress-Induced Phytochemical Production in Lettuce

Lettuce is a very popular and widely consumed vegetable. It ranks high both in production and economic value in many countries, especially the United States. As is the case with many plants, lettuce produces phytochemicals in

response to environmental stress, as a defence mechanism. Specifically, lettuce is high in antioxidants, which play an important role in combating the adverse cell responses that lead to many diseases. Lettuce is also high in a chemical known as 'L-chicoric acid' – a potent inhibitor of human immunodeficiency virus (HIV) integrase, which is needed for the replication of the virus.

Dr Rajashekar and his colleagues wanted to enhance the production of phytochemicals in lettuce by subjecting it to certain mild environmental stresses. The stresses applied included mild heat shock, chilling, and high light intensities.

‘For a long time, people in crop science, both in agronomy and in horticulture, have focused on increasing the crop yields, but quality has always been the secondary objective. What we are trying to do is actually use mild stress on the plants to make them produce more of these antioxidants and phytochemicals, and thereby improve their nutritional quality.’

After applying these stresses, the team found that there was a significant increase in the concentrations of many phytochemicals. Because of these higher concentrations, the team also measured a large increase in the lettuce’s antioxidant capacity – the ability to deactivate disease causing chemicals such as free radicals in humans. The team achieved this effect without causing damage to the plant or negatively affecting yield. In particular, they found that periods of exposure to intense light were quite effective.

Dr Rajashekar and his team are further investigating the impact of the quality of light (including UV) on the accumulation of health-promoting phytochemicals in lettuce and tomato. Using LEDs, they found that specific colours of visible light and UV-A are essential for the production of many phytochemicals in leafy vegetables. As a next step to boost the nutritional quality of these crops in the field, the team is involved in studies to evaluate and select polycovers (polyethylene films) that would allow the appropriate quality of sunlight through in high tunnel productions of these crops.

Different Growth Conditions and Crop Management Practices

In 2010, Dr Rajashekar and his team again visited the idea of inducing enhanced phytochemical production in lettuce using mild environmental stresses. This time, however, they would investigate the effect of specific growth conditions and crop management practices.

First, they applied stress in the form of scheduled water deficits. In another experiment, they applied stress by altering the location, or growing conditions, of the lettuce plants. For example, the team moved the lettuce plants to an open field and monitored the effects of that change. These two experiments showed that, by withholding water and causing water stress on lettuce plants, and by changing the plants’ growing conditions, the concentration of antioxidants in lettuce could indeed be increased. And again, these stresses did not adversely affect physical plant growth and yield.

In addition, the team studied the effect of crop fertilisation, especially involving nitrogen on the quality of leafy vegetables. They found that excessive nitrogen can actually impede the accumulation of many phytochemicals in lettuce and other leafy vegetables.

In recent years, increasing numbers of fruit and vegetable crops are being grown in protected environments such as high tunnels covered with polyethylene sheets, which can alter the sunlight received by these crops. High tunnels are quite popular because growers can expect higher crop yield and extended growing season using these structures. However, Dr Rajashekar and his colleagues have found that high tunnels, despite their popularity, may actually lower the nutritional quality of crops because they alter the light quality that the crops receive.

In 2012, Dr Rajashekar then turned his attention to the use of organic farming practices, and their ability to increase the concentration of health-promoting constituents in lettuce. His team’s focus

was on a compound known as 'L-chicoric acid' – a chemical used in the fight against AIDS, as it can reduce the replication of the HIV virus. They found that the concentration of L-chicoric acid in lettuce grown using organic farming strategies increased nearly 2-fold compared with lettuce grown using more conventional farming practices.

Clearly, growing conditions play a huge role in improving the health benefits associated with many vegetables and their capacity to fight disease. The insights that Dr Rajashekar's team has gathered are bound to improve current crop management practices.

Alfalfa, Broccoli and Radish Sprouts

Just like lettuce, sprouts of alfalfa, broccoli and radish are high in phytochemicals and have a significant antioxidant capacity. Due to this characteristic, according to Dr Rajashekar's research, they can help to decrease the incidence of chronic and degenerative diseases and cancer. However, the phytochemical concentration of these types of sprouts decreases sharply with age. Therefore, their health benefits may significantly decrease by the time they reach consumers. On the other hand, young sprouts, which have a higher nutritional content, are often not robust enough to cope with early harvesting.

For these reasons, sprouts were deemed to be the perfect candidate for applying the method that had been developed. Perhaps the research team could again use mild environmental stresses to increase the phytochemical concentrations of sprouts and ensure that they are maintained for longer periods of time.

The objective of their research was to use certain shocks involving high light intensity and chilling, on sprouts of alfalfa, broccoli and radish, to offset the decline in phytochemicals that occurs with age. As expected, exposing the sprouts to high light intensities or chilling resulted in higher total phytochemical concentration and antioxidant capacity compared with untreated controls. And as was the case with the lettuce experiments, the team found that exposure to high light intensities worked best.

The team's study proved that environmental stresses can be successfully used to enhance the health-promoting qualities of sprouts. Furthermore, given the ease with which the effect can be induced, it would be relatively simple to adopt by sprout growers.

Effect of Increasing Carbon Dioxide on Lettuce and Spinach

Recently, Dr Rajashekar and his team have been focusing on the potential effects of rising atmospheric carbon dioxide levels on plant growth, productivity and nutritional quality. Specifically, in research from 2016, the team examined the impact of elevated carbon dioxide levels on lettuce and spinach. They found that elevated carbon dioxide decreases the concentration of a number of key nutrients. 'It decreases the concentration of nitrogen (protein), phosphorus and potassium along with many important micronutrients including copper, zinc, magnesium and sulphur in either lettuce, spinach or both,' the team stated in their study.

This is rather dire considering that global carbon dioxide levels are on the rise due to fossil fuel combustion and widespread deforestation. Incidentally, however, subjecting lettuce to elevated carbon dioxide levels increased the concentration of some phytochemicals. It appeared that, in this case, ensuring the health-promoting qualities of certain vegetables would be a balancing act between retaining protein and essential mineral nutrient content and producing important phytochemicals.

In a paper of 2018, Dr Rajashekar further investigated this conundrum. His team highlighted that increased carbon dioxide does indeed have a positive effect on plant growth and yield. It can improve drought resistance and water efficiency. Furthermore, it can increase carbohydrate accumulation, which again, stimulates the production of certain phytochemicals. Not only are these chemicals beneficial to humans, they can also fortify a plant's defence strategy against pathogens and herbivory – leading to better crop yields. On the other hand, the team found that elevated carbon dioxide levels lead to the suppression of other nutrients, which could, in turn, result in widespread malnutrition. This presents a real challenge for future fruit and vegetable production, especially given recent developments in terms of climate.

In summary, Dr Rajashekar's work has demonstrated the positive effect of mild environmental stresses on the production of health-promoting constituents in certain vegetables. Specifically, exposure to high and low temperatures, water stress and high light intensities, and adopting appropriate crop management practices (such as planting in open fields and using organic farming strategies), may lead to positive results in this regard. Therefore, as the environment and economy undergo significant change, the work of Dr Rajashekar will no doubt result in better crop management practices to ensure that global citizens have access to more nutritious food in the future.

Meet the researcher

Dr C. B. Rajashekar
Department of Horticulture and Natural Resources
Kansas State University
Manhattan, KS, USA

Dr C. B. Rajashekar received his PhD from Colorado State University, where his research focused on plant responses to environmental stresses and tolerance mechanisms. After completing his PhD, he took a postgraduate position at the University of Minnesota, where he again studied the effect of environmental stresses on plants and their adaptive capabilities. In 1989, he joined the Department of Horticulture at Kansas State University, firstly as an Assistant Professor, later working his way up to full Professor of Food Crops and Phytochemicals. His recent research has focused on how mild environmental stresses and altered farming practices can be used to increase plant phytochemical production and enhance the health-promoting qualities of common fruits and vegetables. He is also investigating the effects of carbon dioxide on plant nutritional content.

CONTACT

E: crajashe@ksu.edu
W: https://hnr.k-state.edu/people/faculty/cb-rajashekar/

KEY COLLABORATORS

Dr Myung-Min Oh, Chung-Buk National University, South Korea
Dr Edward E. Carey, International Potato Center, Peru

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ORANGE INNOVATION: CREATING CITRUS DISEASE RESISTANCE

Florida's citrus industry is under threat from Huanglongbing (HLB, or citrus greening disease), a devastating plant disease. A collaboration between the University of Florida and the University of Connecticut aims to develop resistance to HLB in citrus plants, using conventional breeding and cutting-edge CRISPR gene-editing approaches.

HLB, Enemy of Citrus

Citrus production is indisputably Florida's most important agricultural industry, with over 400,000 acres, worth $9.3 billion annually. But Florida's iconic citrus culture is under threat from a devastating tree disease, known as citrus greening or Huanglongbing (HLB), which is likely caused by *Candidatus* Liberibacter asiaticus (*C*Las) bacteria.

The vector for HLB is the Asian citrus psyllid (ACP) – a member of the psyllid family of sap-sucking insects. The ACP's entire life cycle – from egg to nymph to adult – happens on trees and shrubs of the *Rutaceae* family, including citrus. ACPs suck on sap from shoots, and inadvertently introduce *C*Las into the plant's sugar-transporting phloem vessels. In citrus trees, HLB symptoms include yellowing of leaf veins and a blotchy green-yellow mottling of the leaf blades, twig dieback, stunted growth and eventual death. Afflicted trees bear small, irregularly-shaped, bitter-tasting green fruits with little market value.

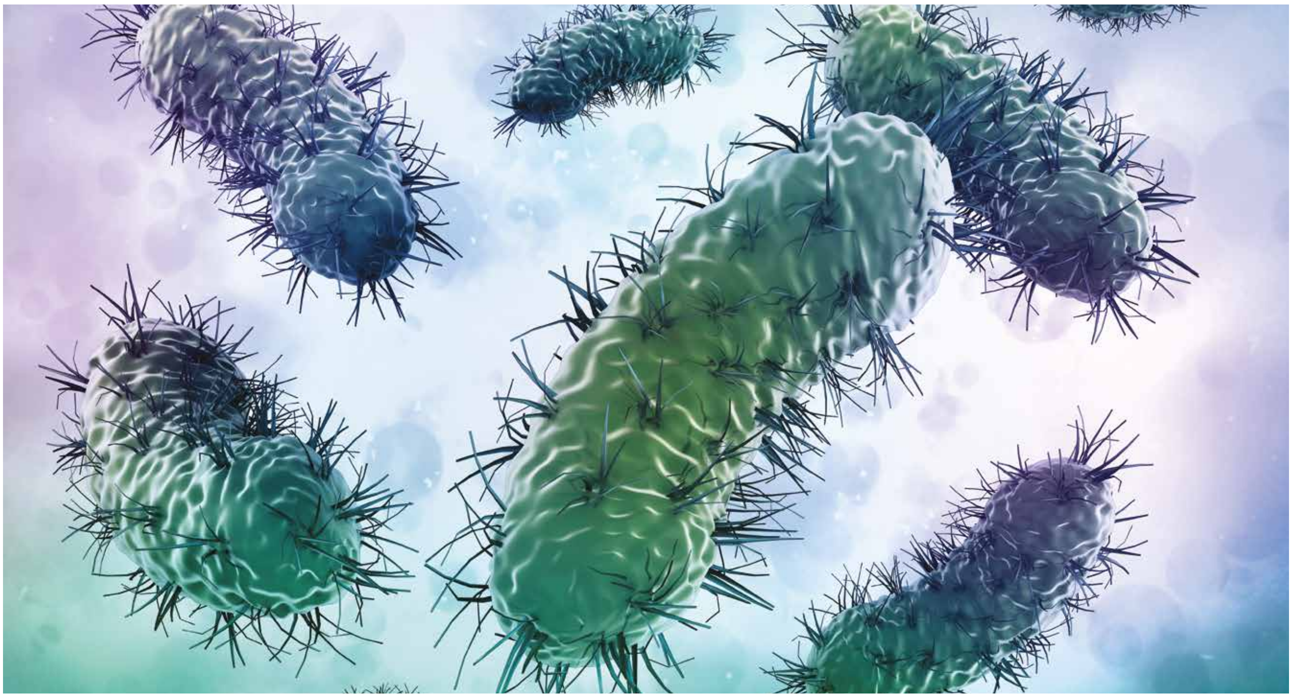
First observed in China in the early 1900s, HLB has decimated citrus groves in many parts of the world, especially in Florida. In fact, the state's citrus production has more than halved since HLB was discovered in Florida in 2005. Unfortunately, HLB is also proliferating rapidly through America's other citrus growing states – California and Texas – which fear they will suffer the same fate.

HLB has hit Florida's economy hard. The extortionate costs of grove maintenance and stock losses has forced many growers out of business. Packinghouses and processing plants have also closed, with significant declines in employment. Recommended management strategies – including using pathogen-free planting stock, insecticides, and removal of infected trees – have had limited effectiveness in Florida because the disease was already widespread prior to its detection. Moreover, psyllids are developing resistance to insecticides. Therefore, farmers have faced two choices: remove their trees and start again or attempt to keep infected trees reasonably productive through horticultural intercessions. The former approach is impractical, and the latter is costly and perhaps unsustainable.

Genetic Approaches to Improving HLB Tolerance

A synergistic collaboration between scientists is attempting to find long-term robust solutions in combatting HLB. The team includes the research groups of Professors Fred Gmitter and Zhanao Deng of the University of Florida, and Professor Yi Li of the University of Connecticut. Using a suite of cutting-edge gene editing, genetic engineering, and breeding techniques, they are attempting to create citrus varieties with intrinsic resistance to HLB as well as other useful agronomic traits.

Sadly, there's no 'cure' for HLB, and no citrus species is known to have complete resistance. 'However, there are different degrees of sensitivity to the disease,' says Professor Gmitter,



'and this offers us hope that plant breeders and geneticists may be able to devise strategies that can lead to the development of very tolerant, or perhaps even resistant, citrus trees.'

HLB plays out at the molecular level in citrus plants, and various plant proteins may be implicated in bestowing tolerance to the disease. Proteins are encoded by DNA (genes), and thus disease-tolerant traits (phenotype) are determined by the plant's genotype. Professors Gmitter, Deng and Li and their colleagues are genetically screening cultivated citrus varieties with high and low tolerance to HLB, to identify which genes (and corresponding proteins) are important in fighting HLB. This information will be useful in selecting genetic targets for breeding HLB resistance into commercial varieties.

The team has had a number of successes in characterising varieties with high tolerance to HLB, which could provide breeding stock for commercial citrus production. These include trifoliate orange (*Poncirus trifoliata*), which hybridises with several commercial citrus species, and rough lemon (*Citrus jambhiri*).

The researchers carried out genotype-phenotype experiments with trifoliate orange and trifoliate orange-sweet orange hybrids ('citrange'), exposing these plants to HLB, and found that the *Poncirus*-derived plants (both 'pure' and hybrid) had low susceptibility to HLB. With cutting-edge genotyping tools, they also mapped the genomes of the citrange hybrids to locate certain 'quantitative trait loci' (QTLs). QTLs are DNA sections that determine specific traits – in this case, the team identified those related to HLB tolerance.

Genes direct the production (or 'expression') of proteins through messenger RNA 'transcript' molecules. The group investigates RNA transcript profiles (the 'transcriptome') to indicate gene expression. Using transcriptomics tools, they have compared the transcriptomes of HLB-tolerant rough lemon with HLB-susceptible sweet orange to determine which genes are 'switched on' to express proteins implicated in disease tolerance. The insights from these studies have led the team to identify genetic 'biomarkers' to aid breeding and genome editing efforts. Also, the team's efforts to characterise the genotype-phenotype relationships will be instrumental to the research community's efforts to rescue the citrus industry.

Breeding Robust Agronomic Traits

Professor Gmitter's research scope extends beyond HLB. 'Our long-range goals include the development of new varieties of citrus that will taste and look better, will be more nutritious, and will be sustainable,' he states. Producers and consumers want fruits that are easy to handle and process, and the group's breeding programs are geared towards these requirements.

In 2015, they developed an early maturing, easy to peel, seedless mandarin variety named 'Bingo'. Recently, they crossed different varieties to produce seedless offspring towards the development of additional new seedless grapefruits and mandarins. A current ongoing project involves developing lemon varieties for improved peel oil production, as well as seedless fruit. To this end, they selected up to 50 lemon varieties from several thousand candidates. They have also planted new rootstock in Florida's citrus groves to evaluate production out in the field. In collaboration with Dr Yu Wang at the University of Florida, they are evaluating oil and juice quality of lemons grown near Vero Beach, Florida – an area where HLB is endemic. Since HLB was first found in Florida, the focus shifted substantially to HLB tolerance.

CRISPR for GMO-free Gene Editing

Conventional selective breeding is slow – often taking several years or decades to obtain varieties with the desired traits. But HLB is an imminent threat – and tough citrus plants that can fight infection are needed as soon as possible. A modern alternative is genetic modification (or 'genetic engineering'). This involves introducing one or more foreign genes from any suitable organism – plant, animal or even microbes – into the plant genome.

Unlike selective breeding, genetic modification (GM) can produce traits not found in the plant population – higher yields, resistance to pests or diseases. GM crops were first introduced in the 1980s and are adopted worldwide – but their uptake is controversial. 'Many consumers and countries have rejected GM foods even though extensive studies have proved they are safe to consume,' says Professor Li.

There is an even newer alternative – CRISPR gene editing. CRISPR was first discovered in 2007 as an RNA-based 'immune system' in bacteria. In the early- to mid-2010s, CRISPR began to be repurposed as a versatile gene editing system for a range of organisms, taking the world of biotechnology by storm. Very early on, the agricultural utility of CRISPR for improving crop plants was realised. CRISPR is much faster than conventional breeding in targeting very specific characteristics – perfect for rapidly engineering resistance against new threats. In collaboration with Professors Gmitter and Deng, Professor Li's research group is actively investigating CRISPR biotechnology in plants, with the long-term plan of applying this to rapidly engineering new traits such as HLB resistance.

CRISPR-modified organisms are generally not regarded as GM. GM involves 'copying and pasting' genes or large DNA sections from other organisms into plant genomes. In contrast, CRISPR gene editing involves directly rewriting the plant's own genetic code by introducing relatively small targeted changes to the DNA – such as insertions, deletions or substitutions. The changes are akin to inheriting a good gene variant – but without the unpredictability of conventional breeding. Hence, CRISPR is far less controversial – both to the public and regulators. In March 2018, the USDA announced that it won't regulate new plant varieties developed by genome editing technologies such as CRISPR that yield plants indistinguishable from those developed by traditional breeding methods – as opposed to GM plants that contain DNA from another organism.

The CRISPR system, derived from bacteria, consists of a protein – Cas9 – which snips DNA, and an RNA molecule that acts as a guide for making minor edits to the DNA code. Like a targeted missile, RNA and Cas9 together locate a specific DNA section of the genome and make changes. The system is precise and surprisingly simple. The standard approach for plants is to insert the CRISPR genes that encode the CRISPR-Cas9 system into the plant's genome, which then expresses the RNA-Cas9 'editing machine' that makes the required genotypic changes. But this presents a catch-22, as inserting the bacterial CRISPR gene into the plant would make it a GM crop.

Therefore, the research team has developed a CRISPR plant application that does not introduce foreign bacterial genes into the plant's genome – using *Agrobacterium tumefaciens* to deliver the CRISPR-Cas9 system instead. *Agrobacterium* is a soil bacterium that naturally associates with plants, commonly used in plant biotechnology. They engineered the *Agrobacterium*'s DNA to express the CRISPR RNA-Cas9 'editing machine', and incubated the bacteria with tobacco leaves together. The bacteria infect the plant cells and deliver the gene-editing machinery, which rewrites the genetic code. The *Agrobacterium* DNA does not become part of the plant's genome, so CRISPR genes cannot be passed down through plant generations.

The researchers were able to regenerate whole plants from the edited plant cells after a few weeks or months – far quicker than the years it takes with conventional breeding. The *Agrobacterium* CRISPR process is fairly easy – but the hardest part is diagnosing whether gene editing was a success. The team has developed a clever method for the rapid, expedient screening of CRISPR-modified plants, using high-throughput DNA screening to identify whether the plant tissues have the required genomic edits.

The team's revolutionary approach to *Agrobacterium*-mediated CRISPR for plant gene editing could be used to circumvent current legislation and rapidly develop GM-free crop traits indistinguishable from those achieved through breeding efforts. The collaborative team hopes to use the CRISPR gene editing to create robust citrus varieties that fight off HLB, without compromising other traits desired by producers and consumers.

Meet the researchers

Professor Fred G. Gmitter, Jr.
Citrus Research and Education Center (CREC)
Institute of Food and Agricultural Sciences
University of Florida
Lake Alfred, FL
USA

Professor Fred G. Gmitter Jr. earned his PhD in Horticultural Sciences in 1985 at the University of Florida, where he is currently a Professor at the Citrus Research and Education Center. He is a citrus breeder focused on developing new rootstock and scion cultivars. His research is aimed towards supporting Florida's citrus industry with fruits that are robust, easy to process, disease-tolerant, delicious and aesthetically pleasing. He has released and patented several elite cultivars. Professor Gmitter deploys classical and contemporary genetic and genomic approaches to improve efficiency of breeding programs, while maintaining focus on cultivar development and release.

CONTACT

E: fgmitter@ufl.edu
W: http://www.crec.ifas.ufl.edu/academics/faculty/gmitter/

Professor Zhanao Deng
Gulf Coast Research and Education Center (GCREC)
Institute of Food and Agricultural Sciences
University of Florida
Wimauma, FL
USA

Professor Zhanao Deng obtained his PhD in Horticulture at Huazhong Agricultural University, China, in 1988. He is currently a Professor at the University of Florida, where he specialises in ornamental plant and fruit breeding and genetics. His research is geared towards developing new plant cultivars for Florida growers and consumers. His current breeding efforts are directed toward the developing and releasing new caladium and lantana cultivars, genetic sterilising lantana and nandina, and developing biotechnological tools to speed up genetic improvement of horticultural plants for disease resistance.

CONTACT

E: zdeng@ufl.edu
W: https://gcrec.ifas.ufl.edu/faculty/dr-zhanao-deng/

Professor Yi Li
Department of Plant Science and Landscape Architectures
University of Connecticut
Storrs, CT
USA

Professor Yi Li obtained his PhD from the State University of New York. He is currently a professor in the University of Connecticut, with research in the areas of plant physiology, biotechnology and breeding. He has developed a number of transgenic (genetic modification) and gene editing technologies, including seedless fruit technology, gene deletor technology, grafting enhancing technology, and several new horticultural plant cultivars. He has received more than $8 million in research grants, and his research has been extensively covered by the media.

CONTACT

E: yi.li@uconn.edu
W: http://plantscience.uconn.edu/People/Faculty/Y.Li.php

KEY COLLABORATORS

Professor Richard J. McAvoy, University of Connecticut
Dr Ziniu Deng, Hunan Agricultural University

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WHEN VIRUSES INFECT PLANTS

Just as human beings can catch a cold, plants can also get viral infections. Understanding the mechanisms regulating the interactions between plants and viruses is the first step towards developing better management strategies and using biotechnology methods to immunise plants and engineer genetic resistance to viruses in plants. This is the focus of research by **Dr Hernan Garcia-Ruiz** and his team based at the University of Nebraska, USA.

Viral diseases in plants can cause important economic losses as a result of poor-quality products and lower yield. This impact can particularly seriously affect developing countries which are more likely to be dependent on agricultural production to ensure food security for the population. Additionally, the strict sanitary regulations which are in place to avoid the spread of diseases across countries may limit the international trade of agricultural products, compounding the impact of plant viral infections.

How Do Plants Catch Viruses?

Plants (crops, medicinal or ornamental), can be infected by viruses. It all may start with an insect bite. The virus only has to reach a single cell to initiate infection. However, as viruses cannot do anything by themselves, they need to hijack the infected cell's mechanisms to produce copies of themselves. Eventually, progeny viruses are released to neighbouring cells and this cycle is repeated. Soon the virus is able to reach the vascular system in the plant (akin to the circulatory system in animals) and can spread long distances from the initial spot of infection, infecting everything from roots to young leaves.

Humans and animals have an immune system to fight viral infections. Interestingly, plants have an immune system too. In plants and insects, a very effective way to combat a virus is through a process known as gene silencing. This mechanism treats a virus as a gene that is being expressed out of control. Thus, plant cells turn it off by dicing the viral RNA into small pieces. This shuts down the infection by restricting the movement of the virus into new cells in the plant or the ability of the viral RNA to make more copies. A remarkable feature of this mechanism is that infected cells can send a signal to neighbouring cells thus activating antiviral defences even before arrival of the virus. This mechanism requires a series of proteins that normally participate in the regulation of cellular gene expression.

Unfortunately for plants, viruses don't give up easily and have a few extra tricks up their sleeves. As a way of counteracting the gene silencing deployed by the plants, viruses can also produce special proteins with the power to interfere with plant defences. This can be achieved through several mechanisms. The target for destruction, or inactivation, is always one or more of the elements involved in the plants' defence response.

Credit Hernan Garcia-Ruiz

Credit Hernan Garcia-Ruiz

Credit Hernan Garcia-Ruiz

Deciding who wins this battle largely depends on the balance between antiviral gene silencing from the plant versus suppression of this mechanism by the virus. The determinants of this fight and its outcome have been the focus of intense research during the last ten years. Dr Hernan Garcia-Ruiz and his team are driving forward important research informing the identification and characterisation of cellular factors that condition susceptibility to plant viruses. Their project uses model plants and RNA viruses to determine the mechanisms of antiviral gene silencing. This work will help define how viral RNAs are recognised as distinct from cellular (non-targeted) RNA and determine the mechanisms of antiviral gene silencing.

How Do Plants Fight Viral Infections?

We know that plants fight infection by using gene silencing although the original signal that indicates the presence of a viral infection remains a mystery. However, work by Dr Garcia-Ruiz and his team has shown that once a plant has detected a virus, the main objective is to dice and degrade the viral RNA to avoid the spread of the disease. This complex process essentially relies on a series of proteins which can target and destroy viral RNA.

In plants, the defence mechanism against viral infections is more complicated than previously thought. It is not simply a matter of identifying the proteins involved. There are multiple layers of complexity in the plants' response. For example, plants may have a preferred path, but in its absence, there is always a Plan B. In this case, a second set of proteins is able to come forward and defend the plant (even if sometimes it is not as effective as the main system).

In addition, some proteins seem to act more efficiently in protecting certain locations in the plant, such as leaves or flowers, for example; while others have a strong response irrespective of the specific location. Some work alone, while others work better in co-operation with multiple proteins.

Ultimately, whether the fight against the virus is successful or not depends on a delicate balance of all these mechanisms working at the same time. Understanding this response is essential for understanding how plants normally resist viruses, why some viruses are highly virulent in different hosts, and how sustainable antiviral resistance strategies can be deployed in agricultural settings.

Retaliation of Viruses

To complicate things further, viruses don't just take the attack. In retaliation to the plants' response, viruses can trigger their own counterattack. This is achieved by multiple mechanisms, including a search and destroy of all plant proteins involved in their defence mechanism. However, each virus has its own arsenal of weapons and the exact mechanisms for each case are yet to be discovered.

Healthy maize (shown on the left) and maize with lethal necrosis disease (shown on the right). Credit Hernan Garcia-Ruiz

Complexity of Viral Infections in Plants

Sometimes plants get infected by multiple viruses. This combination could trigger a stronger mechanism to block any defence and result in a perplexing set of symptoms, as shown by Dr Garcia-Ruiz's analysis of maize plants affected by lethal necrosis in Kenya.

Detected in the 1970s in Kansas and Nebraska, maize lethal necrosis is caused by a synergistic co-infection of maize chlorotic mottle virus combined with sugarcane mosaic virus, wheat streak mosaic virus or Johnson grass mosaic virus. Typical symptoms include yellow leaves dried from the edges, smaller plants which can also be sterile, and malformed or rotten cobs.

However, in 2017, in farmer's fields in Kenya, Dr Garcia-Ruiz and his team detected plants showing bright yellow stripes with green edges, which deviate from typical maize lethal necrosis symptoms. It turns out the plants in Kenya were infected with a combination of two, three, or four viruses, including a virus called maize yellow mosaic virus, which may explain the different symptoms. To make things worse, sorghum, napier grass, and possibly other plants can also be infected, making management of this disease very difficult.

These results highlight the huge complexity underlying the maize lethal necrosis epidemic in Kenya. A critical aspect that needs further research is to understand how the viruses act together to fight the plants' response. From the practical point of view, as this disease continues to spread and is becoming a major concern for farmers, work by Dr Garcia-Ruiz and his team is only the starting point. Further investigation is needed to determine the role of silencing suppression, and the contribution of different viruses to maize lethal necrosis, in order to develop more accurate virus diagnostic protocols and new management strategies.

A Challenge for the Future

Researchers have identified a few cases of natural genetic resistance which they have managed to introduce into commercial cultivars. Unfortunately, this only applies to a few examples. For many diseases affecting staple crops, plants don't have any genetic resistance to viral infections. The good news is that using the latest genetic techniques, including genome editing, and artificial gene silencing, it is now possible to engineer virus resistance in plants to boost their immune system. Although underpinned by different mechanisms, this concept is similar to that of a vaccine. To improve the efficiency of these approaches, it is necessary to elucidate the mechanisms that allow the plant to recognise the presence of a virus and the sneaky ways viruses can avoid the plants' response.

Some viruses cause important human diseases, others cause devastating diseases in primary staple crops, causing multi-billion-dollar loses worldwide and threaten food security in some parts of the world. The ultimate challenge for plant pathologists, such as Dr Garcia-Ruiz, is to translate all this knowledge acquired in the lab into practical and effective applications that will enable farmers to fight plant disease.

Meet the researcher

Dr Hernan Garcia-Ruiz
Assistant Professor
Department of Plant Pathology and Nebraska Center for Virology
University of Nebraska
Lincoln, NE
USA

Dr Hernan Garcia-Ruiz obtained his PhD in molecular virology from the University of Wisconsin-Madison in 2006. His mentor during this time was Dr Paul G. Ahlquist. Dr Garcia-Ruiz then completed postdoctoral research at the Oregon State University Center for Genome Research and Biocomputing with a Helen Hay Whitney fellowship. During this time, his mentor was Dr Jim Carrington. After working as a Research Scientist for three years at the Donald Danforth Plant Science Center, Dr Garcia-Ruiz joined the University of Nebraska-Lincoln in 2014 as an Assistant Professor in the Department of Plant Pathology. Dr Garcia-Ruiz's laboratory focuses on investigating the molecular mechanisms of antiviral immunity in plants, particularly the mechanisms of viral RNA replication, gene silencing, and their interconnections.

CONTACT

E: hgarciaruiz2@unl.edu
W: https://plantpathology.unl.edu/hernan-garcia-ruiz

CURRENT FUNDING

National Institutes of Health
United States Department of Agriculture

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THE MOLECULAR WORLD OF APHID FEEDING

Professor Gerald Reeck and his team at Kansas State University are investigating the molecular basis of aphid herbivory, including suppression of plant defences, using powerful methods of molecular genetics. This research is important for developing new aphid-pest resistance strategies for crop plants.

You have probably seen tiny green insects, about a millimetre in length, jostling on the stem of your back-garden beanstalk. These little critters are aphids, and they feed on plant sap. As sap-suckers, aphids occupy a special ecological niche, and the damage they inflict on crops does not endear them to farmers.

Aphids are typically fussy eaters, having narrow food preferences. For instance, the Russian wheat aphid feeds on wheat and barley, whereas the pea aphid is a pest of peas, beans and alfalfa. The appearance of aphids on the evolutionary scene predated the advent of flowering plants by 100 million years, so the first aphids are thought to have fed on more primitive plants. Aphids belong to the *Hemiptera* order of insects. All 'hemipteran' insects, including aphids, have specialised mouthparts called stylets, which allow them to pierce plant tissues and suck out the sap.

Plants make sugars and complex carbohydrates using Nature's most basic ingredients – water, carbon dioxide from the air and photons from sunlight – during photosynthesis. Photosynthesis occurs mainly in the leaves, but the sugars produced here are required as a respiratory fuel by other tissues. Therefore, plants have a network of tubes, known as 'phloem', which is composed of columns of living cells known as 'sieve elements' that transport dissolved sugars and other biochemical compounds from the leaves to other tissues.

Aphids feed directly on phloem sap, by inserting their specialised mouthparts into the plant's phloem and ingesting the sap by sucking. Plants are not too thrilled about their sap being tapped by freeloading aphids, and have evolved a number of defence responses against insects. Hemipterans, such as aphids, have in turn evolved strategies to evade plant defences, and for millions of years, plants and aphids have been locked in an evolutionary arms race.

The evolution of plant-eating insects is driven by the plants they feed on. The opposite is also true, as such insects have affected plant evolution – most obviously the development of flowering plants with insect-mediated pollination. Plants have evolved a molecular 'immune system' to defend against herbivores and pathogens. However, insects – as well as fungal and bacterial pathogens – produce 'effector' molecules that attempt to override the host plant's defences to facilitate feeding or colonisation. This has given rise to an evolutionary 'standoff'.

One of the numerous groups investigating these fascinating processes is led by aphidologist Professor Gerald Reeck at Kansas State University, who is attempting to elucidate the molecular interactions between aphids and host plants – using the pea aphid as a model organism. As the first aphid to have its genome sequenced, the pea aphid is a popular choice for studying aphid biology and aphid/plant interactions.

As several aphid species are serious agricultural pests, his team's insights will be important in answering key questions about aphid biology, leading to improved

The console of a pipe organ with about 70 stops. The stops are the round knobs or buttons to the left and right of the keyboards. When pulled out, the stops activate pipes (not shown). The organist would typically select 10–20 stops as a group to create the sound desired for a given piece of music or for a particular passage from a piece. The pipe organ is the origin of the common phrase 'pull out all the stops,' but in reality an organist would never do that, and Professor Reeck suggests that an aphid would never simultaneously express all 100 of the genes that encode proteins of saliva.

strategies to control aphid infestations of crops. 'Besides the fascinating issue of the co-evolution of aphids and their host plants,' explains Professor Reeck, 'the detailed nature of aphid feeding is important for developing new approaches (beyond treating plants with chemical insecticides) for controlling infestations by aphids and other hemipterans.'

Aphids as Skilled 'Pipe Organists'

Aphid feeding is a precise and orchestrated process. When an aphid lands on a leaf or stem, it will typically spend up to 60 minutes initiating its feeding. This involves penetrating its stylet into the leaf, and probing through the intercellular space until it finds and punctures into a phloem sieve element. The aphid will then suck the sugary sap for up to several hours without re-positioning.

Traditionally, aphidologists have supposed that there are just two types of saliva, but Professor Reeck and his colleagues are developing the view that there are in fact numerous types of saliva. Aphid saliva can contain up to 100 different proteins – more than enough to create and secrete many different salivas, each with its own protein composition.

But why so many different salivas? These must be related to an aphid's ability to 'make a living', explains Professor Reeck. An aphid must deal with numerous different types of feeding situations, and as saliva allows an aphid to feed, an aphid must therefore be able to create numerous different types of saliva.

As well as enabling the aphid's fairly complicated pursuit of a sieve element and tapping into the 'life-giving elixir' that is phloem sap, aphid species often feed on various host plants. Sometimes, aphids attempt to resort to feeding on non-host plants if their preferred foods are not available. This ability to secrete saliva with differing protein compositions is therefore seen as an evolutionary trait allowing aphids to adapt to feed on several different plant species.

Professor Reeck likes using a 'pipe organ analogy' to illustrate this. A skilled organist can create many different sounds with a pipe organ by selecting different subsets of an organ's 'stops'. Similarly, aphids can create different salivas using different subsets of the 100 proteins that can potentially be secreted from their salivary glands. 'Thus, an aphid makes its living by playing the pipe organ (the organ that is its salivary gland)!' states Professor Reeck.

Powerful Approaches for Studying Aphid-Plant Interactions at a Molecular Level

An organism's proteins are encoded by its genes. During gene expression, the information in the genes (DNA) is 'transcribed' onto messenger RNA molecules (also called 'transcripts') that dictate the order in which amino acids join together (and their specific order, or

sequence) to form individual proteins. Using a 'transcriptomics' approach, Professor Reeck's team studies the sequences in transcripts for the proteins of aphid saliva (the transcriptome). From this information, they infer the amino acid sequences of the individual proteins in aphid saliva. They call this collection of proteins the 'saliva secretome'.

As well as sexual reproduction leading to females laying fertilised eggs, aphids also reproduce asexually. Adult asexual aphids produce nymphs, which grow into adults. The offspring are all female and clones of their mothers – with no males involved! When host plants are abundant, either in nature or in the laboratory, asexual reproduction by aphids can result in hundreds of aphids feeding on an individual plant. In the lab, this asexual reproduction is a useful feature for producing large colonies for scientific studies.

Pea aphids are fragile, soft-bodied and tiny – about the size of a grain of sand! To study the proteins in their saliva and the encoding transcripts, Professor Reeck and his team dissect the salivary glands of several hundred pea aphids. To analyse the transcriptome, the team extracts all of the RNA from the dissected salivary glands, and using a technique called 'reverse-transcription PCR', creates a 'library' of corresponding DNA molecules. (This is essentially the reverse of what happens in cells, where the information in DNA is transcribed to produce messenger RNA during gene expression.) The resulting DNA library is subjected to sequencing to identify mRNAs that encode proteins of saliva.

So, how can we learn about the role or importance of an individual protein in feeding on a host plant? One of the most powerful approaches is called 'transcript knockdown'. Using this technique, scientists can deplete aphids' salivary glands of the mRNA that codes for an individual protein. Professor Reeck and his colleagues made the first finding of this sort in aphids by applying this technique to a protein that they call Protein c002. By injecting a piece of double-stranded RNA (dsRNA) into many individual aphids (and injecting control insects with an innocuous dsRNA), they demonstrated that Protein c002 is required for the pea aphid to feed on bean plants. They also found that the death of the c002-targeted insects was similar to death by starvation. The team has more recently obtained similar results for a protein called Armet, and further injections of dsRNA are underway in Professor Reeck's laboratory (and other labs as well).

What Lies Ahead

Aphid infestations can cause significant damage to several major crop plants. And if we expand our horizons a little, the same can be said of other hemipteran species such as planthoppers, leafhoppers, whiteflies and psyllids. Currently, the main approach for controlling all of these hemipteran pests involves the use of chemical insecticides. We might ask whether we can develop another type of tool, one that will not contaminate the environment with chemicals.

A possible approach involves genetically engineering aphid-resistance into crop plants. This approach has been spectacularly successful for controlling other (non-hemipteran) insects. For instance, maize with excellent resistance to the corn earworm has been created by placing, in the plant's genome, a bacterial gene that encodes a protein that is toxic to lepidopteran insects. However, scientists have yet to find bacterial proteins that are toxins for hemipterans.

Therefore, we must find a different type of gene to introduce into the genome of, say, alfalfa to provide resistance against the pea aphid. 'One possibility is to create a gene that would produce dsRNA in the plant, particularly in the phloem sap,' says Professor Reeck. 'If the dsRNA were targeted at a crucially important aphid protein, the aphid would be taking in a sort of poison in sucking phloem sap from the engineered plant.'

Work in Professor Reeck's lab and other labs around the world suggests that we might be able to identify attractive targets in the saliva proteome of an aphid species. Indeed, Protein c002 might be just such a protein. It would be relatively straightforward to synthesise a dsRNA-encoding gene targeted at Protein c002. The expression of this gene, when incorporated into the pea aphid genome, would result in dsRNA being deposited in the phloem sap, which would be imbibed by the insect. Finally, the dsRNA would need to become distributed throughout the aphid and some of it taken up by secretory cells of the salivary glands in order to knock down Protein c002's transcript. This could lead to death of the aphid, or at the very least, to decreased fecundity.

'Our current results suggest that dsRNA in the diet (even when protected by protein capsules called BAPCs) does not become distributed throughout the aphid but remains in the gut,' says Professor Reeck. 'We are currently working to circumvent this problem and thus open an era of genetically engineered resistance to aphids.'

Meet the researcher

Professor Gerald (Jerry) Reeck

Department of Biochemistry & Molecular Biophysics

Kansas State University

Manhattan, KS

USA

Gerald Reeck received his PhD in biochemistry under the supervision of Hans Neurath in the Department of Biochemistry at the University of Washington in Seattle. He then did post-doctoral research at the National Institutes of Health, where he studied non-histone proteins of chromatin. Since 1974, he has been on the faculty at Kansas State University. He began investigating the biochemistry and molecular genetics of insects in the early 1990s, having been drawn into the field by Professor John Reese of the Department of Entomology at K-State. Their laboratories' joint contributions have been in the transcriptomics of salivary glands of the pea aphid and the use of transcript knockdown through RNAi in the same species. More recently, Professor Reeck has turned his attention to the feeding of dsRNA by forming complexes with peptide capsules as developed by another K-State colleague, Professor John Tomich.

CONTACT

E: grreeck@gmail.com

W: http://www.k-state.edu/bmb/department/directory/reeck/index.html

KEY COLLABORATORS

Dr John Reese, Kansas State University (emeritus)
Dr James Balthazor, Fort Hays State University
Dr Raman Chandrasekar, Kansas State University
Dr Feng Cui, Chinese Academy of Sciences
Dr Le Kang, Chinese Academy of Sciences
Dr John Tomich, Kansas State University
Dr Owain Edwards, CSIRO
Dr James Carolan, University College Dublin

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Kansas State University

CONTROLLING INSECT PESTS WITH RNA INTERFERENCE

Professor Paul Dyson and **Dr Miranda Whitten** at Swansea University in the UK are developing insect pest control methods using endosymbiotic bacteria that target the insects 'from within' using RNA interference.

The *Insecta* class of arthropods is the most diverse group of animals, with over 1.5 million known species. Insects have adapted to numerous worldwide habitats, and play vital roles for ecosystems. For example, they are food for a range of carnivores and recycle a variety of organic matter, and thus are vital components of complex food webs. Countless flowering plants could not exist without them, relying on flying insects for essential pollination. Worryingly, global insect biodiversity has declined precipitously in recent decades, due to climate change, habitat loss, pollution and intensive agriculture.

The ecological activities of insects often put them in conflict with humans. Human pathogens spread by insect vectors account for a massive 15% of all infectious disease cases. Annually, half of global crop production is lost to insect pests. Despite their decline, some hardy populations are actually expanding, including 'undesirables' such as the Western Flower Thrips and *Aedes aegypti*, a mosquito vector of arboviruses such as Zika.

The post-World War II development of synthetic pesticide compounds represented a major victory in our millennia-old spat with our six-legged foes – though not without collateral damage. Insecticides have proved effective at reducing pest numbers and improving crop yields. However, chemical insecticides are usually indiscriminate, affecting numerous other species, including beneficial organisms.

Insecticides often kill pollinators and aquatic larvae, with disastrous consequences for predatory animals, such as birds. Moreover, there has been concern about the impact of pesticides on human health. Some notoriously destructive insecticides are now banned or restricted, most famously DDT due to its toxic accumulation in birds of prey. Currently, there is now global pressure to restrict neonicotinoid insecticides due to their well-documented bee-killing ability.

The mass application of insecticides leads to the evolution of insecticide resistance in target insects, greatly reducing their effectiveness and posing major threats to global food supply and public health. A widely advocated alternative to agriculture's reliance on chemical pesticides is 'integrated pest management'. Integrated pest management schemes make use of biological control agents such as predatory insects, nematodes, insect-pathogenic fungi or insecticidal bacteria to reduce pest numbers, though these have had moderate effectiveness.

One such scheme involves a soil bacterium called *Bacillus thuringiensis* (Bt), which is a 'living insecticide', producing endotoxin proteins that are toxic to several insect species when ingested. For a century, Bt spores and endotoxin preparations have been applied to crop pests and disease vectors. In the last two decades, genetically modified Bt crops have been developed, which has involved inserting Bt toxin genes into plants so they produce their own insecticidal proteins.

Two notable successes are Bt corn, regarded as safe for human consumption but deleterious to the European corn borer and corn earworm pests, and Bt cotton, which resists the infamous bollworm. Together, Bt varieties account for 75% of US acreage of corn and cotton. However, just like chemical insecticides, these strategies lead to pest resistance.

RNA Interference for Pest Control

Professor Paul Dyson, Dr Miranda Whitten and their colleagues at Swansea University, Wales, are aiming to reduce the dependence of global agriculture on

Electron microscope image of a juvenile Western Flower Thrips

pesticides, using a different type of biotechnology. They are developing a new anti-insect technology known as 'symbiont-mediated RNA interference', which exploits symbiotic bacteria found inside insects.

Professor Dyson is a molecular microbiologist with an interest in repurposing bacteria – at the molecular level – for practical applications. Dr Whitten is a molecular entomologist, with a keen interest in the molecular basis of insect biology, behaviour and ecology. Ten years ago, Dr Whitten and Professor Dyson embarked on their highly synergistic collaboration, first using 'RNA interference' (a process in which RNA molecules inhibit gene expression) to study gene function in insect model organisms. The pair then turned their attention to non-model insects such as agricultural pests.

It is often said that the best way to defeat an enemy in combat is to infiltrate from within. This is certainly true in the team's approach to RNA interference, by targeting the insect's gene-to-protein expression 'from within'. An organism's DNA genome is composed of gene sequences that encode the set of proteins to be expressed, so an insect's genome is therefore a good starting point. The technology is timely as it can exploit the results of the 5000 Insect Genome Project (i5K), a global scheme to sequence the genomes of 5000 species of insect and other arthropods (http://i5k.github.io/arthropod_genomes_at_ncbi).

Inside cells, information flows from genes to protein production in 'transcripts' – linear molecules known as messenger RNA (mRNA). mRNA transcripts have a sequence complimentary to a corresponding gene sequence, and these diffuse from the cell's genome to ribosomes – the cellular protein 'factories' – where the transcripts dictate the assembly of various amino acids into chains to form functional proteins.

However, this tightly regulated process of protein expression can be blockaded by small double-stranded RNA (dsRNA) molecules, known as 'small interfering RNAs' (siRNAs) – a mechanism exploited in RNA interference. Inside cells, double-stranded longer dsRNAs are enzymatically 'diced' into short fragments, the siRNAs, each of which has one strand removed and the remaining strand (complimentary to the mRNA transcript) binds to the transcript, priming it for destruction. The targeted mRNA is therefore prevented from being 'translated' into protein. For RNA interference in insects, external dsRNAs are supplied to the organism, which can reduce (knock-down) or even completely stop (knock-out) the production of a certain protein that an organism requires to carry out an important function.

RNA interference is a fairly new tool with promising applications in biotechnology and medicine. Conventionally, dsRNAs and siRNAs are supplied to the organism by microinjection – a highly tedious and labour-intensive operation – or by soaking the organism in a medium containing the dsRNAs. Another option is to genetically engineer certain bacteria to express specific dsRNAs, and feeding these bacteria to insects to knock out the gene of interest. This approach was first pioneered by other labs in the common model organisms *Caenorhabditis elegans* and then in *Drosophila*, using the bacterial model *Escherichia coli.* However, Dr Whitten and Professor Dyson were the first to use this technique in non-model insects and with symbiotic bacteria.

In the wild, insect species often develop interesting relationships with endosymbiotic bacteria that colonise the insect's gut. These bacteria are speculated to synthesise a range of compounds beneficial to the insect's survival, such as B vitamins. Professor Dyson, Dr Whitten and their colleagues have been investigating the utility of these naturally occurring endosymbionts for delivering dsRNAs to the insect.
Two such insect-gut living endosymbiontic bacteria investigated by the team are *Rhodococcus rhodnii* (isolated from the insect *Rhodnius prolixus*) and BFo2 (a newly characterised

Kissing bugs feeding on symbionts in horse blood

Enterobacteriales species isolated from the Western flower thrips). In the lab, they have cultured and genetically engineered these bacteria so they express dsRNAs that are detrimental to insect protein expression. Such dsRNAs are tailored to be specific to a particular pest, and should not directly affect other insects in the ecosystem, or the health of human consumers. The team's symbiont-mediated RNA interference strategy, if delivered effectively, can be cost-effective, fast acting, and with the advantage that the symbiotic bacteria continuously produce dsRNAs in their host. As the bacteria can be engineered to produce dsRNAs to target multiple genes this approach is unlikely to lead to the evolution of pest resistance.

Assassinating Assassin Bugs and Tripping Thrips

Triatomine insects, also known as kissing bugs, assassin bugs or vampire bugs, feed on the blood of vertebrates, including humans. Triatomine insects typically host parasitic organisms known as trypanosomes, such as *Trypanosoma cruzi*, the causal agent of Chagas disease. Chagas disease, endemic in parts of South and Central America, is a potentially fatal tropical disease that can lead to failure of the nervous, digestive and cardiovascular systems.
All triatomine insects are potential vectors of Chagas disease, though species well-adapted to living with humans, such as *Triatoma infestans* and *Rhodnius prolixus*, are the main vectors. The prevention of Chagas disease is a major priority, and Professor Dyson and Dr Whitten, in collaboration with the University Federal Fluminense and the Instituto Oswaldo Cruz, Brazil, are working towards its prevention by targeting the *Rhodnius prolixus* vector.

Having fed genetically engineered *Rhodococcus rhodnii* to lab-grown *Rhodnius prolixus* (via horse blood!), the team found that insects produced fewer offspring, and had reduced feeding activity. The dsRNAs supplied to the insects through the bacteria knocked down the insects' nitrophorin proteins, important salivary anticoagulants, and vitellin, a protein involved in egg production. These findings demonstrate a promising vector control strategy to reduce the spread of Chagas disease.

The Western flower thrips has surged outwards from its native southwestern USA into every cultivated continent in just six decades. This insect is a major agricultural pest, inflicting tremendous damage to several crops through its feeding and egg-laying behaviours. Thus, its effective management is an urgent agricultural priority, and the team has focussed on developing their symbiont-mediated RNA interference strategy to defeat this troublesome critter. Having fed recombinant BFo2 to larval and adult thrips, the infected insects were observed to inflict significantly less damage to the leaves of cucumber seedlings through the knock-down of tubulin protein expression. Spraying crops with dsRNA-expressing symbionts may provide an effective, pest-specific alternative to pesticides for the control of thrips damage.

Summary and Future Directions

Global agriculture and disease prevention is seeking new effective alternatives to the pesticide paradigm. Professor Dyson and Dr Whitten are proposing a biotechnological solution, symbiont-mediated RNA interference, and their initial results prove promising. The team is currently investigating the biological basis of the transfer of dsRNAs from the bacteria to the insects, in order to improve efficacies. They are also collaborating with international groups to develop symbiont-mediated RNA interference strategies against diseases such as Dengue and Zika spread by *Aedes* mosquitoes, and sleeping sickness spread by tsetse flies.

Whilst insects can be pests, they are also important components of global ecosystems, and the team's approach provides a means of targeting the 'bad critters' with minimal collateral damage.

Meet the researchers

Professor Paul Dyson
Institute of Life Science
Swansea University Medical School
Swansea
Wales, UK

Professor Paul Dyson is a molecular microbiologist with research interests in exploiting bacteria for biotechnological and medical applications. His ongoing collaborative research themes include exploiting the genetic potential of antibiotic-producing Streptomyces bacteria to produce new antibiotics, exploiting symbiotic bacteria to control agricultural pest insects and insect vectors of human diseases, and utilising tumour-colonising bacteria for therapeutic means. He has been at Swansea University since 1989, where he started as a Lecturer, rose through the ranks as a Senior Lecturer and Reader, before gaining his Professorship in 2007.

CONTACT

E: p.j.dyson@swansea.ac.uk
W: http://www.swansea.ac.uk/staff/medicine/learningandteaching/dysonpj/

Dr Miranda Whitten
Institute of Life Science
Swansea University Medical School
Swansea
Wales, UK

Dr Miranda Whitten is a molecular entomologist whose main research interest is in host-pathogen interactions and biocontrol strategies of insects. She made significant contributions to our understanding of the role of lipoproteins in insect immunity, and following her postdoctoral training in insect reverse genetics with Nobel Laureate Prof Jules Hoffmann, she worked with Imperial College researchers to understand how mating alters female mosquito physiology. In recognising the practical limitations of reverse genetics tools for non-model insects, she instigated a collaboration with Dr Paul Dyson to develop symbiont-mediated RNA interference strategies, and soon thereafter joined the Dyson group. Dr Whitten has supervised several Masters and PhD students, has fieldwork experience in sub-Saharan Africa, and is Scientific Advisor for the university spin-out company Bionema.

CONTACT

E: m.m.a.whitten@swansea.ac.uk
W: http://www.swansea.ac.uk/staff/medicine/research/walkerm/

KEY COLLABORATORS

Chinese Academy of Sciences, Lanzhou
Tehran University
Liverpool School of Tropical Medicine
University Federal Fluminense and the Instituto Oswaldo Cruz, Rio de Janeiro, Brazil

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BUZZING & BLOOMING: BEE-FLOWER INTERACTIONS IN CROP PRODUCTION

Pollination by flying insects is often the forgotten key to high agricultural productivity. **Dr Johanne Brunet,** research ecologist at the USDA-Agricultural Service, is investigating insect-flower interactions, and their implications for crop production.

Bees as Agricultural Pollinators

Many crop plants are propagated by sexual reproduction, which is often slow and cumbersome as it involves the orchestrated processes of flowering, pollination, fertilisation, seed production and sowing. But sexual reproduction can also promote genetic diversity, leading to crop populations that are more resilient to harsh or changing environmental conditions – such as frost, diseases and pests.

Pollination is a critical step in crop propagation – especially in fruit farming, where the fruits themselves are the product of flower fertilisation. This process involves the transfer of pollen grains from the male part (stamen) to the female part (stigma) of flowers. Upon reaching the stigma, the pollen grain travels down a tube to the ovaries, where fertilisation occurs – the fusion of eggs and pollen – which leads to the production of seeds.

Although many flowering plants rely on the wind to transfer pollen grains, a large proportion of our crops are entirely dependent on insect pollination. The vast majority of fruits and vegetables, especially when one considers seed production, are pollinated by insects. But how do plants get flying insects to act as pollen delivery agents? Flowers produce pollen and nectar, which act as food for flying insects. When insects fly from flower to flower, collecting nectar or pollen, pollen attaches to their bodies, and is then transferred between flowers.

Bees are the most common managed agricultural pollinators, especially honeybees, although the use of solitary bee species is on the rise. Bumblebees and several other wild bee species can also play an important role in the pollination of certain crops. Unfortunately, populations of wild and managed bees are steadily declining – with worrying implications for global agriculture.

Destruction of wild habitats has had devastating impacts on wild bee populations. Honeybees, the most commonly used managed pollinator in agriculture, are suffering from ‘colony collapse disorder’ – whereby worker bees do not return to the hive. The lack of workers results in the death of the colony as the young are no longer cared for. Many factors, including stress and disease, appear to be responsible for this collapse. Moreover, the application of broad-spectrum insecticides to crops, such as neonicotinoids, can also negatively impact both wild

and managed bee populations. It is clear that bee conservation must be prioritised, as the loss of bees would be devastating to our global food supply.

Investigating Bee-Flower Mutualism

The pollinator-flower mutualistic interaction that plays out in crop pollination has massive ramifications for human food supply. This interaction is more complex than we might think, and scientists have made great strides in understanding it. Yet, much of this still remains shrouded in mystery. Elucidating some of these mysterious details is part of Professor Johanne Brunet’s research goals. Flowering plants – known as angiosperms – are thought to have emerged 120 million years ago. Since then, the evolution of angiosperms and insects has been inextricably linked, and this ancient mutualism has driven profound changes

in both. Professor Brunet and her group are investigating this complex mutualism between plants and their pollinators.

Flowers are effectively giant advertising displays to entice passing flyers. Among flowering plants there is extraordinary diversity in floral display, shape and colour – features that are important in attracting pollinators. Even within a population, there can be great variation in flower colour and the size of floral displays.

Although honeybees and bumblebees exist as part of highly organised colonies, they exhibit individualistic and complex learned behaviours. They can learn to associate a flower colour with nectar or pollen payoffs. When nectar or pollen payoffs are similar between different flower colours in a population, bees often modify their innate colour preferences. Bees' preferences for flower colour and morphology have been a lively research theme for Professor Brunet's group.

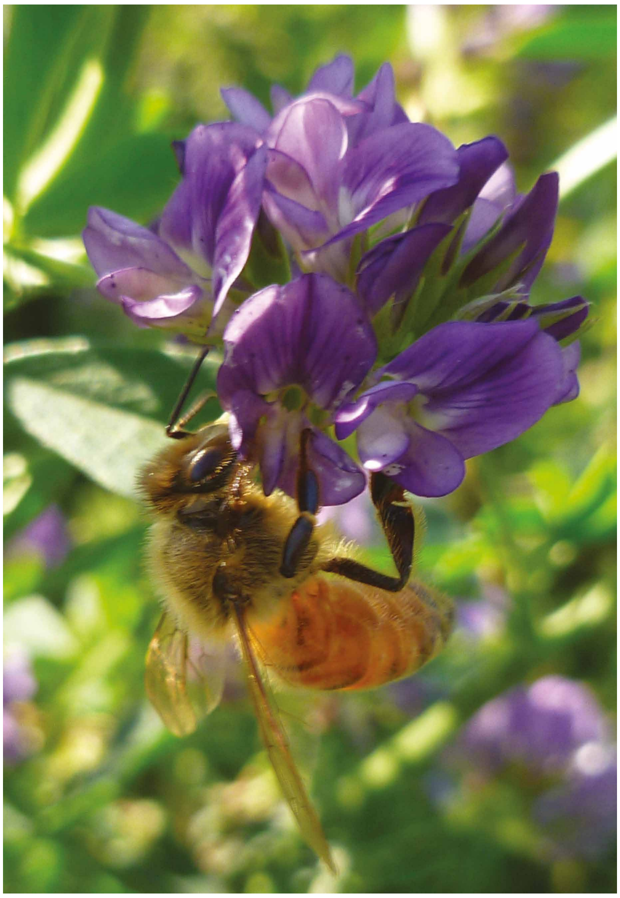
A Bee's-Eye View of the Alfalfa Agroecosystem

Professor Brunet and her team currently investigate these bee-flower interactions in alfalfa. Alfalfa is a perennial forage crop used to feed livestock for grazing, hay and silage. As it is a legume, the crop is able to convert nitrogen in the air into soluble nitrates or ammonia, helping to maintain soil fertility. For Professor Brunet, alfalfa is an ideal model species for investigating pollinator-flower interactions, as it is highly dependent on insect pollination for seed production. Also, the plants exhibit varying numbers of flowering stems, racemes (clusters of flowers) per stem and flowers per raceme – creating a large variation in floral display size, and thus great variation in food rewards for the bees. There is also great variation in flower colour – ranging from shades of purple to white to yellow.

The research team carries out many of their field studies at the West Madison Agricultural Research Station in the heart of Wisconsin's alfalfa territory. For their field studies, the team germinates alfalfa seeds in the greenhouse before transplanting the seedlings in the field. The group seeks to obtain a 'bee's eye view' of the alfalfa agroecosystem. A large component of their research involves stalking bees in the field and observing their foraging behaviour – from a distance to avoid confounding the bees' natural behaviour. They study visitations from three different bee species – the European honeybee, alfalfa leaf-cutting bee and common eastern bumblebee.

The group meticulously records the floral characteristics of each alfalfa plant – no easy feat – and over a fortnight at peak-bloom, they wait for foraging bees. When a bee is spotted in a field, the plants it lands on are recorded, as well as the number of racemes per plant, and the number of flowers per raceme visited by the bee. Six weeks later, they collect seeds on the plants. The team then runs the data from these field observations through powerful statistical models, allowing them to gain deep insights into the relationship between the flowers' attractiveness to bees and the alfalfa crops' reproductive success.

The findings of their field studies have been insightful. They found that plants with larger floral displays received more bee visits, and this was true for all three bee species. Flower colour affected the number of visits from bumblebees and honeybees, but not leaf-cutting bees. Interestingly, honeybees changed their preference of flower colour from one year to the next. The team speculates that honeybees' high levels of bee-to-bee communication and strong learning abilities could help explain such switch in colour preference. The



team also revealed a correlation between bee visits and alfalfa seed production – attesting to the importance of bees as crop pollinators – with leaf-cutting bees being the most effective pollinators, followed by bumblebees, and lastly honeybees.

Pollinator Behaviour and Gene Flow

'An important research area in the laboratory examines the link between pollinator foraging behaviour and gene flow,' states Professor Brunet. 'We are interested in the patterns of bee movement from flower to flower, from plant to plant and from field to field and the accompanying pattern of pollen movement as the pollen is moved by the bees,' she says. When the pollen and egg fuse together in fertilisation, the offspring plant will inherit genes from both parents. Therefore, the transfer of pollen grains, clinging to the hairs of a flying bee's body, from flower to flower, moves genes over the landscape. When a seed is produced following pollen transfer between flowers, a 'gene flow' event has occurred.

Professor Brunet and her team found that leaf-cutting bees, while foraging within a field, tend to move randomly between flowers, racemes and plants. They also discovered that honeybees and bumblebees typically tend to move in the same direction during foraging – which is known as 'directionality' of movement. Bees that exhibit directionality of movement obviously move greater net distances than those that randomly change directions – thus moving pollen and genes further.

Aside from directionality of movement, Dr Brunet and her team have identified or confirmed other foraging behaviours that affect gene flow. One such behaviour is the number of flowers visited by a bee in a field. Visiting more flowers within the same field actually tends to limit gene flow, as pollen grains from one flower tend to all be deposited on the flowers in that field.

The 'tripping rate' also influences gene flow. Tripping occurs when a pollinator depresses the keel of a flower in order to expose the stigmas for pollen to be released. Bee species vary in their tripping rate (the proportion of flowers visited that are tripped) and those with the highest tripping rate are predicted to have lower gene flow. This occurs because pollen is not deposited or collected from untripped flowers and the distance travelled by the individual pollen grains therefore increases.

Bee movements between fields must also be considered. Professor Brunet believes that bees do not pre-plan their itinerary before leaving the hive, but must decide where to go next every time they move between fields. This decision-making process may be random, or may be based on information about field size, field isolation or a combination of these two factors. The team is currently investigating the decision-making process of bees as they move between fields.

Thus, gene flow depends very much on bees' foraging behaviour, and Professor Brunet's group is investigating. In collaboration with Dr Murray Clayton, also at the University of Wisconsin–Madison, they are modelling bee foraging to predict gene flow. The model has first been developed for continuous landscapes (one large field) and after the bee decision-making process has been elucidated, the team will expand their model to discontinuous landscapes (many fields).

Some types of alfalfa have been genetically engineered (GE) to confer practical traits, such as herbicide resistance, or low lignin to increase digestibility to cattle. GE alfalfa is common in the US, though there are concerns about gene flow between GE and non-GE varieties through pollination, leading to gene contamination of non-GE alfalfa crops destined for the conventional, organic and export markets. Therefore, the group has been measuring bee-mediated gene flow using GE alfalfa in order to test their model. They hope, on one hand, to apply the model of bee foraging to predict gene flow and, on the other, to use knowledge of bee foraging behaviour to develop management practices that limit GE gene flow.

Therefore, Professor Brunet's work will improve the coexistence of GE and non-GE crops that rely on insect pollination. In addition to this, the team's new insights into how different bees forage in agricultural fields and how this influences bee nutrition will help to promote bee survival and conservation.

Meet the researcher

Professor Johanne Brunet
USDA-ARS Vegetable Crops Research Unit
Department of Entomology
University of Wisconsin
Madison, WI, USA

Professor Johanne Brunet gained an MS degree at McGill University in 1987 and a PhD at the State University of New York (SUNY) at Stony Brook in 1990. Upon graduating, she took up various research and teaching positions at the University of Chicago, University of Washington, Oregon State and Willamette University, focusing mainly on plant mating system evolution and plant-pathogen interactions. In 2003, she joined the USDA Agricultural Research Service and became Assistant Professor in the Department of Horticulture at the University of Wisconsin–Madison. Here, she rose to the ranks of Associate Professor and then full Professor in the Department of Entomology. Her research interests include the evolution, biology and ecology of pollination, plant-pollinator interactions, pollinator-mediated gene flow, and the implications for agricultural productivity and GM crop containment. Some of her group's recent projects have focused on investigating pollinator movement and patterns of pollen deposition, the visual and olfactory cues of flowers that influence bee visitation, and identifying relationships between pollinator behaviour, plant traits, self-pollination and crop yields. Aside from her research, she has also been active in journal editorial duties, scientific outreach, consultancy and advisory panels.

CONTACT

E: Johanne.Brunet@ars.usda.gov
E: jbrunet@wisc.edu
W: http://labs.russell.wisc.edu/brunet/

USDA Agricultural Research Service

KEY COLLABORATORS

Dr Murray Clayton, University of Wisconsin–Madison
Dr Heathcliffe Riday, USDA-ARS

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WATER CONSERVATION

CONSERVING WATER IN THE FACE OF CLIMATE CHANGE

According to the *Intergovernmental Panel on Climate Change*, the rising temperatures associated with global warming will wreak havoc on all aspects of Earth's water cycle. Already, we are beginning to notice these effects – with many regions around the world experiencing increasingly frequent and severe droughts and flooding. Such intensified periods of drought are already leading to worrying water shortages worldwide, while increased incidences of severe flooding events can contaminate water sources and even destroy the infrastructure we use to transport water.

As about 70% of all our freshwater withdrawals are used for agricultural purposes, such disturbances to water availability have worrying consequences for our growing population's increasing food demands. For example, in many parts of the world, massive swathes of irrigated cropland rely on snowmelt and mountain glaciers for water – but these frozen reservoirs are becoming smaller each year, while their melting patterns become less predictable.

In the near future, the amount of water feeding rivers and aquifers will experience shocking declines in semi-arid areas of the Americas, Australia and Africa, as well as the Mediterranean, severely affecting availability in these regions. Everywhere, rising temperatures mean that crops require more irrigation to survive and thrive – thus, climate change is increasing water demand while shrinking water supplies.

More than ever before, we need novel solutions to ensure the sustainability of our water resources into the future, which will offset the rising pressures posed by climate change and population growth. However, such approaches to meeting our increasing water demands must not further negatively impact ecosystems, as emphasised by The United Nations World Water Development Report 2018.

Therefore, this section of the edition showcases the work of several researchers who are working to adapt our agricultural systems to conserve water, while also protecting and restoring the local environment. We also meet researchers who are developing new ways to forecast drought with increasing accuracy, to save lives and livelihoods.

First in this section, we meet Dr Laurent Ahiablame at the University of California Division of Agriculture and Natural Resources. His team works with farmers, communities and policy makers to identify low-impact methods for both agriculture and urban development that improve water conservation while protecting human health and the environment. Using rigorous computational modelling, Dr Ahiablame and his colleagues also assess how water availability and quality may change under various future climate scenarios.

Also seeking to develop novel approaches for better managing our water systems is an interdisciplinary team of researchers from Kansas State University, who we meet in the next article. This team is trying to find new ways to better manage the watersheds of the Central Great Plains – a region located in the central and southern region of the US. Approaching the problem from the viewpoints of various

disciplines, the team hopes to improve water conservation and environmental quality, ensuring that clean water is available to future generations and that local biodiversity is protected. Their approach is sure to continue to inform better decision and policy making both in the Central Great Plains and the rest of the world.

On the topic of water policy, next we focus on assessing how effective policies are for managing our increasingly scarce water resources and associated ecosystems. Here, we introduce the work of researchers from the Agrifood Research and Technology Center (CITA), the University of Zaragoza, the International Institute for Applied Systems Analysis, and the University of California Riverside, who have carried out extensive research estimating the impacts of different policies on the performance of river basin ecosystems, with a particular focus on the Jucar River Basin in Spain.

Our next featured research team focuses their efforts on the Colorado River Basin, a critical source of water for local agriculture, people and the environment. Here, we meet the Colorado State University team, who has been working with Colorado River Basin agricultural producers and water managers to address one question in particular: 'can agriculture cooperate with other sectors to meet water shortages without compromising their ability to produce food and maintain the viability of rural amenities we all enjoy?'

Next, we introduce an interdisciplinary team of researchers from New Mexico State University, the University of New Mexico, Sandia National Laboratories and the New Mexico Institute of Mining and Technology, who have been investigating a traditional type of irrigation system called an acequia, found in the arid southwestern US. Such acequias, which mimic seasonal streams and provide valuable wildlife habitats, may help to counteract the negative effects of a changing climate on regional water cycles. Therefore, the research team worked closely with acequia communities to understand their resilience and adaptive capacity in the face of emerging threats.

The last article in this section showcases the work of the Climate Hazards Group, who are helping to predict droughts and resulting food shortages among the world's most vulnerable populations. Through the ability to predict which areas will be most likely to endure drought or other food-limiting climatic events, the team supports critical planning and timely humanitarian assistance that save lives and livelihoods in Africa and beyond.

HOW DOES CLIMATE CHANGE INTENSIFY WATER SCARCITY?

Greater variability in precipitation often leading to long periods of drought interspersed with periods of heavy rainfall

Shrinking of mountain glaciers – leading to diminishing water reserves

Intense periods of rainfall can cause flooding – damaging infrastructure used to transport water

More severe and longer periods of drought – leading to an increased need to irrigate crops

Increased evaporation from reservoirs, lakes and wetlands – diminishing resources

Sea level rise – causing salt-water intrusion into freshwater reservoirs and contaminating reserves

Greater rates of evapotranspiration from cropland – leading to an increased need for irrigation

BALANCING AGRICULTURE & URBAN DEVELOPMENT WITH WATER MANAGEMENT

Our vital water resources are under heavy pressure as the world's population continues to expand rapidly. Coupled with challenges associated with climate change, the water management discussion has never been more relevant. **Dr Laurent Ahiablame**, from the University of California Division of Agriculture and Natural Resources, works with farmers, communities and policy makers to find low-impact methods for urbanisation and farming that improve water management while protecting human health and the environment.

Throughout history, urban development, agriculture and hydrology – the study of the Earth's water – have been at odds. Urbanisation often focusses on moving water rapidly out of urban areas, wreaking havoc on local and even regional hydrological systems. Human-made surfaces and artificial drainage systems effectively convert large amounts of rainfall into surface runoff. While this may be useful for the city centre, it has considerable consequences for the areas receiving this influx, resulting in flash-flooding events.

Dr Laurent Ahiablame and his colleagues work at the interface between urban and rural water management and are extensively involved in 'low-impact development', or LID. The aim of LID is to more sensitively manage the water planning of an urban area by mimicking the natural hydrological processes of infiltration, evaporation and storm water storage. LID technologies include permeable pavement, vegetated swale and other water management techniques at the source.

By applying water management models to different types of watersheds, Dr Ahiablame's team can assess the potential role of LID practices in reducing flooding in light of predicted climate and land-use changes. In central Illinois, for example, the team estimates that urban land use over the study period of 1992–2030 will increase from 50% to 94%, with a coincident increase of 30% in average annual runoff and flooding events.

In this case study, the researchers found that the implementation of three LID practices – porous pavements, rain barrels and water gardens – resulted in a 47% reduction in runoff within the watershed and a reduction of up to 40% in flooding events. In scenarios within two Indianapolis watersheds where porous pavements and rooftops connected to rain barrels were implemented at a rate greater than 25%, storm-water runoff and increased baseflow (shallow subsurface flow) decreased significantly, which further resulted in slight decreases in pollutant loads (as an added benefit). These studies highlight how modelling can be used to inform the management and decision-making policies of land developers looking to install LID practices within a watershed.

Agricultural practices such as irrigation and artificial drainage may increase direct connectivity between fields and streams, potentially reducing longer subsurface pathways. In both urban and rural areas, a great need exists for water-sensitive designs and sustainable drainage systems that conform to the watershed's natural condition.

Land Use and Climate Change

Watershed models can also be used to study how future climate and land-use changes might affect a given watershed, since climate and land-use changes usually produce changes in a watershed hydrology. Climate observations over the last century indicate that some areas are likely to see an intensification of the hydrological cycle, with more

'We all live in a watershed, and what we do in our own yard will eventually affect everyone around us and downstream.'

frequent extreme temperature and precipitation events – ultimately impacting local and regional water resources.

Dr Ahiablame led a study investigating land-use and climate-change effects on the hydrology of the agricultural watershed of the James River in the Upper Midwest US. Using a number of general circulation climate models with coupled ocean and atmosphere components, his team generated several climate-change scenarios for 20-year periods in the mid- and late-21st century, and a land-use forecasting model with corresponding predicted-land-use maps. Using the Soil and Water Assessment Tool (SWAT) model, they next quantified the impacts of these two factors on the watershed's hydrological processes. In order to assess the dominant drivers, the scenarios were designed using a fixed climate with shifting land use, then a shifting climate with fixed land use, and finally, a changing climate and changing land use.

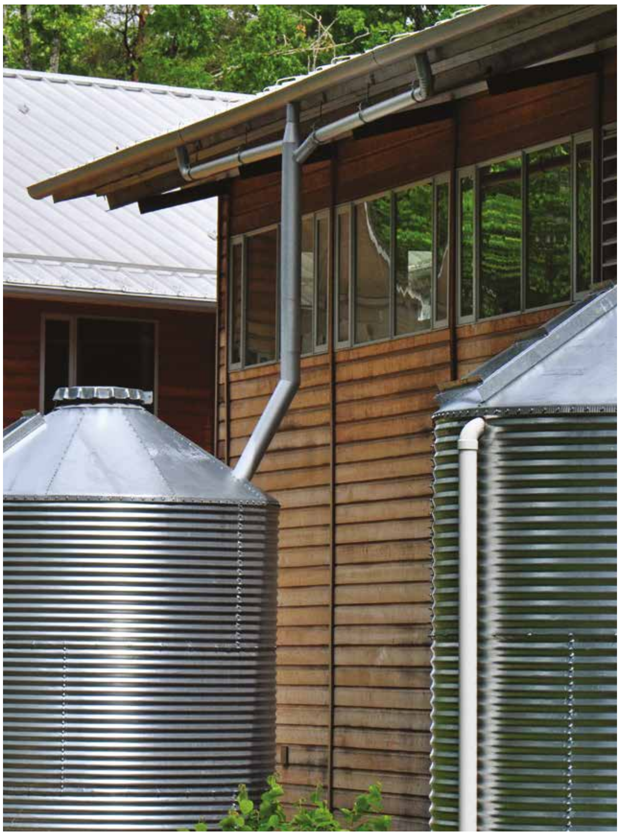
The team's results indicated that climate change was a stronger driver than land-use change for increasing the annual streamflow within the catchment (17–41% and 12–18% increases, respectively) by the end of the century. Together, the combined effect of land use and climate change intensified the discharge increase within the catchment rivers. Increased streamflow can induce increased subsurface flow, which has documented impacts on water quality and soil nutrient levels. As one of the team's 2017 papers in the Journal of Hydrology states: 'Such local and regional studies are needed to increase understanding of economical, societal, and environmental implications of land-use change in the face of a changing climate.' They conclude that such studies are 'a call for researchers, practitioners, and policy makers to be well prepared to adopt best practices in water resources management.'

Statistics and Hydrology

Dr Ahiablame is also heavily involved in establishing statistical and GIS techniques to study how and why hydrological systems change over time. Such studies increase our knowledge of how such changes might impact water resources.

In one such study, Dr Ahiablame and his colleagues analysed the long-term baseflow records of the Missouri River Basin from 1950 to 2014. Their results highlighted that baseflow was the dominant contributor to streamflow in the basins (at 60%), but also revealed an upward trend in baseflow and precipitation during the study period. The team concluded that changes in precipitation exerted a stronger influence on baseflow than changes in agricultural land use – an important consideration for future management and decision making.

Further afield, in the Limpopo River Basin (LRB) in Southern Africa, Dr Ahiablame and collaborator Dr Esther Mosase studied the spatial and temporal trends in the rainfall and temperature data from 1979 to 2013. The LRB covers vast swathes of Botswana, Zimbabwe, Mozambique and South Africa, where millions depend on its waters. However, the basin experiences extreme seasonality and is affected by strong El Niño-Southern Oscillation events. As a result, precipitation across the basin is highly variable, both spatially and temporally. The researchers concluded that while the increasing trend in rainfall suggests increasing water availability, increases in the population and changes in land use and agricultural intensity continue to put pressure on the system and its water resources. The team highlighted the



need for increased awareness within the planning community to develop greater resiliency against water risks in the basin.

Agricultural Water Quality Protection

Artificial subsurface drainage in agricultural water-abundant regions plays an important part in regulating soil moisture and maximising crop growth. However, such drainage also leads to nutrient losses and changes in surface land cover and groundwater. Lost nutrients are carried in drainage waters and collected downstream in nearby lake and river systems. These excess nutrients, in particular phosphorous and nitrogen, are key drivers behind eutrophication – a process wherein water quality is rapidly deteriorated by excess nutrients that foster uncontrolled growth of plants and algae that consume the water's oxygen.

As Dr Ahiablame himself says: 'We all live in a watershed, and what we do in our own yard will eventually affect everyone around us and downstream.' Along with colleagues and students, Dr Ahiablame is currently exploring best management practices (BMPs) for reducing both nitrogen and phosphorus in agricultural drainage waters to protect downstream water resources. Improving fertiliser management and application is an important piece of the puzzle; however, it is often insufficient to actually solve the problem. Therefore, much of the team's work involves designing and assessing new methods to remove excess nitrogen and phosphorus from surface and subsurface drainage waters at the earliest possible stage.

Dr Ahiablame and one of his students explored the use of denitrifying woodchip bioreactors and phosphorus-adsorbing structures in their study region. They created these denitrifying bioreactors in trenches filled with carbon-rich material (wood chips) into which subsurface drainage water could flow. Physical and biological reactions then converted the nitrogen compounds within the waters into nitrogen gas, which was released to the atmosphere. The team's phosphorous-adsorbing structure is composed of filters that contain materials rich in phosphorus-loving elements such as aluminium and iron, which were placed near drainage outlets. These elements react and bind with phosphorus to create insoluble compounds, effectively removing it from the water.

Results from this study in eastern South Dakota showed a 7–100% reduction in nitrogen compounds and a 10–90% reduction in dissolved phosphorus. While the effectiveness varied, the results are nonetheless encouraging and provide valuable insight into understanding the most effective ways of managing nutrient removal at the input site, particularly when considering costs.

Prior to field implementation, Dr Ahiablame and his colleagues routinely conduct laboratory experiments to inform their field studies. For example, prior to the field study mentioned above, his team extensively assessed phosphorus removal methods in the lab by comparing the effectiveness of different reactive permeable filters, including natural minerals such as limestone and a number of recycled industrial by-products of steel. They concluded that the relatively inexpensive steel by-products acted as effective adsorption materials for dissolved phosphorus removal and could be combined with woodchips to simultaneously remove nitrogen.

In recent decades, the role of climate change has also been a major focus in watershed management. Dr Ahiablame and his colleagues used future land-use change models in conjunction with SWAT to assess how water quality may change in a given climate and land-use change scenario. In South Dakota, they made an interesting discovery: in some areas, land-use changes may not always be detrimental to water quality. The researchers found that the predicted change in land use in this region shifted towards lower-input agriculture, with hay and pasture production increasing over high-input cultivation, resulting in reduced surface runoff, sediment, nitrate and phosphorous. Their study highlighted how modelling can be used to inform land-management practices in the face of a changing climate and land use.

As we've seen, Dr Ahiablame and his colleagues strive to improve methods of water management and water quality while protecting human health and the environment. Through low-impact farming and low-impact urbanisation, they continue to develop myriad ways of mitigating our footprint on the environment and ensure water security while also protecting the health and safety of future generations.

Meet the researcher

Dr Laurent Ahiablame
University of California
Division of Agriculture and Natural Resources
San Diego Office
USA

Dr Laurent Ahiablame completed his BS in Bioenvironmental Engineering at North Carolina Agricultural and Technical State University in 2006. He moved to Indiana to pursue a Master's degree at Purdue University, where he subsequently took a PhD position and graduated in 2012. For his graduate studies, Dr Ahiablame was awarded the Outstanding PhD Student prize in 2012. In 2013, he moved to Southern Illinois University, Edwardsville, as an Assistant Professor and then to South Dakota State University in 2014 as a Grassland Hydrologist and Assistant Professor. In 2017, Dr Ahiablame moved to his current position at the University of California, where he works as the Director of Agriculture and Natural Resources Division San Diego Office and Water Quality/Management Advisor. Dr Ahiablame has been an active member of the American Society of Agricultural and Biological Engineers since 2006 and has advised many research students.

CONTACT

E: lmahiablame@ucanr.edu
E: lmahiablame@ucdavis.edu
W: http://cesandiego.ucanr.edu/cooperativeextension/contact/?facultyid=37970
W: https://scholar.google.com/citations?user=H5RJb08AAAAJ&hl=en

KEY COLLABORATORS

Bernie Engel, Purdue University, West Lafayette, IN
Indrajeet Chaubey, Purdue University, West Lafayette, IN
Daniel Moriasi, Agricultural Research Service, El Reno, OK
Aleksey Sheshukov, Kansas State University, Manhattan, KS
Vahid Rahmani, Kansas State University, Manhattan, KS
Ryan Bailey, Colorado State University, Fort Collins, CO
Srinivas Janaswamy, South Dakota State University
Esther Mosase, UC Agriculture and Natural Resources, San Diego, CA
Guanghui Hua, South Dakota State University, Brookings, SD
Amir Haghverdi, University of California Riverside, CA

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University of California
Division of Agriculture and Natural Resources

AN INTERDISCIPLINARY APPROACH TO WATER MANAGEMENT

According to the WHO, half of the world's population will be living in water-stressed areas by 2025. Therefore, managing our water resources is vital, especially in a changing climate. On that front, an interdisciplinary team from Kansas State University, led by **Dr Marcellus Caldas** and **Dr Melinda Daniels** from the Stroud Water Research Centre, seeks to understand how human-environment interactions and climate change affect water management and sustainability on the Central Great Plains of the United States.

CREDIT: Sarmistha Chatterjee

A Diverse Team United by One Goal

Approximately 29% of the global population do not use a safely managed drinking-water service – that is, one located on premises, available when needed, and free from contamination. As climate change and its effects continue to grip the planet, the WHO estimate that half of the world's population will be living in water-stressed areas by 2025. These statistics certainly emphasise the importance of being water wise and preserving the resources we have for future generations.

Preserving water resources requires better water management practices. However, understanding and insight is needed to make sure that water management, along with the associated decision-making and policy, is effective. Dr Marcellus Caldas of Kansas State University is part of an interdisciplinary team that includes more than nine researchers across three colleges and six departments – who are working to gain this understanding and insight.

What is notable about their goal is that it seeks to develop a more holistic approach to water resource management – one that incorporates many different viewpoints and areas of expertise. In fact, from the outset, Dr Caldas has emphasised the need for such an approach. 'These are the kind of problems you cannot solve in just one discipline,' he says. 'One factor affects another. Each person is connected in his or her own field and contributing a piece to solve this puzzle.'

The puzzle they are trying to solve is how to better manage the water systems of the Central Great Plains, located in the central and southern region of the United States. As team member and agricultural economist Dr Jason Bergtold says, their main goal is to 'better understand the social, economic, biological and environmental linkages between ourselves and the environment and how we can manage our natural resources.' This sentiment again highlights the need for a more holistic approach to meet the challenge – hence the formation of an interdisciplinary team.

Managing the Watersheds of the Central Great Plains

A watershed is an area of land that catches precipitation and channels the water to local streams and rivers, and eventually into larger bodies of water such as reservoirs, bays, or the ocean. There are many watersheds in the Central Great Plains, such as the

‘These are the kind of problems you cannot solve in just one discipline. One factor affects another. Each person is connected in his or her own field and contributing a piece to solve this puzzle.’

CREDIT: Sarmistha Chatterjee

Smoky Hill watershed, on which the local community relies. However, the watersheds in the region have had longstanding water quality and quantity concerns because of extreme climate variability, intensive water use and land use. ‘Both human and natural systems in this area depend on adequate freshwater for survival,’ explains geographer Dr Melinda Daniels, ‘but they are fragile, quickly and dramatically affected by climate fluctuations, and potentially face disaster given either natural or human-driven climate scenarios.’

Biologist Dr David Haukos also explains that, ‘variations, impacts or loss of water in Great Plains water systems have the capability of producing cascading effects.’ Therefore, members of the team have focused their research on understanding the hydrological characteristics of the region and feeding that back into model development and policy creation. This, in turn, ensures that any subsequent decisions regarding water management and sustainability in the region are effective. If successful, these insights could also help other nations around the world to improve their water management protocols.

The Importance of Research and Regular Feedback

In a study carried out by team member Dr Aleksey Sheshukov and his colleagues, the researchers made the point that, ‘hydrologic observational data are required to conduct implementation and assessment of watershed and water resource management practices, including natural resource planning, flood and drought mitigation, and reservoir operation among other conservation efforts.’ Furthermore, if environmental outcomes are to be achieved, then data collection systems need to be regularly reviewed and improved.

To highlight that this is very much the case, consider the findings of the research described above. To give some background, a network of land-based weather stations has been typically used as a primary source of climate input for agro-ecosystem models on the Smoky Hill watershed. However, the research team’s analysis showed that an alternative data collection model generated smaller bias and could significantly improve simulated streamflow estimates. Clearly, if these improved estimates were to be included in models, and the subsequent decisions in regard to managing the resource, then outcomes would likely be better for both the environment and land owners.

Consider another example. In another research project, team members Dr Daniels and Dr Sheshukov analysed the flow of a semiarid river basin in the Central Great Plains from 50 and 100-year projected climate data. The projected data for these two periods were then compared with historical data to determine changes in flow.

The results from this analysis indicated a significant alteration of water flow. Their findings were also consistent with previous studies of climate change and flow alteration in other regions, predicting shifts in flood timing and magnitudes, significant influences on ecological processes, and potential altering of aquatic ecosystems. This in-depth knowledge of both the historical and predicted conditions of the watershed and associated flow systems would obviously be useful in developing subsequent water resource management practices.

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Incorporating Social-Cultural Perspectives

Incorporating social and cultural perspectives into environmental decision and policy making is also important, yet often neglected. As was highlighted by Dr Caldas and his colleagues in an opinion article published in 2015 in the *Proceedings of the National Academy of Sciences*, 'no matter how extensive and sophisticated our biophysical knowledge, policy institutions, and economic projections, any facet of the environment is difficult to sustain if stakeholder groups are using different cultural frames, and hence meanings or interpretations, of it.'

It has always been the goal of the team, therefore, to develop practical measures to ensure that these social-cultural inputs are understood and taken into consideration. As engineer Dr Jessica Heier Stamm says, 'my hope is that our research will lead to advances in the extent to which local culture and decision objectives can be represented.'

Social science, therefore, is an important part of the equation. In research published in 2017, sociologist Dr Matthew Sanderson highlighted that understanding the role of humans in water systems is necessary to address water resource problems. In response to that challenge, he and his colleagues developed a model that incorporates elements of social science into environmental planning. By doing so, the model captures diverse social and cultural feedback from the human environment, and frames this against feedback from the natural environment. In addition, a model like this could ensure that the scope of decision making is extended from the individual level, which is not necessarily representative, to the group or system level.

The Merits of an Interdisciplinary Approach

One of the notable feature of the team's work is that it brings together experts from completely different areas of study. The researchers, who include geographers, engineers, biologists, economists and sociologists, have collaborated to reach a common goal – to prevent future water scarcity and water quality problems on the Central Great Plains of the United States.

Commenting on the success of this project, ecologist Dr Martha Mather states that 'the unusual and diverse combination of expertise exhibited by our research team has produced a unique dataset that meshes ecological, hydrological, geomorphological, sociological, and economic data on water systems in the Great Plains. This unprecedented dataset can produce new insights and potentially even create transformative paradigms about human impacts on resources and better ways to communicate interdisciplinary research to scientists, the public, and agricultural stakeholders.'

Indeed, the research team, in bringing together their different areas of expertise, has developed a more holistic approach to environmental management – one that centres on robust scientific research and effective models for incorporaing social-cultural perspectives. The team will look to extend the applications of their models and use them to inform better policy. They will also continue to collect data to help support effective decision and policy making. Other members of the team, such as Dr Joe Aistrup, are committed to addressing issues pertaining to irrigational water use and developing graduate education programs so that students better understand water sustainability in the region.

Although approaching their research from a whole range of different angles, the team's goal is unified, and it is clear. They hope to improve water quality in the Central Great Plains to ensure that clean water is available to future generations and that aquatic biodiversity is protected. Their interdisciplinary approach to this challenge is most notable and is sure to continue to inform better decision and policy making both in the Central Great Plains and the rest of the world.

Meet the researchers

Dr Marcellus Caldas
Dr Marcellus Caldas is an economic/environmental geographer and K-State leading principal investigator. Dr Caldas leads the land-use/land-cover and water-use decisions and directly supervises human systems.
E: caldasma@ksu.edu

Dr Jessica Heier Stamm
Dr Jessica Heier Stamm leads the effort to develop a computational framework for policy analysis to incorporate stakeholders' decision-making perspectives and biophysical system models.
E: jlhs@ksu.edu

Dr Jason Bergtold
Dr Jason Bergtold is an economist studying social, economic and ecological factors impacting community support of environmental policy, as well as land-use change and management.
E: bergtold@ksu.edu

Dr Matt Sanderson
Dr Matt Sanderson helped to develop the cultural facets of the human systems component of the integrated model.
E: mattrs@ksu.edu

Dr Martha Mather
Dr Martha Mather's contribution to this collaboration has been to quantify instream biodiversity and link fish data to hydrology, land-use, and human systems.
E: mmather@ksu.edu

Dr Melinda Daniels
Dr Melinda Daniels is an interdisciplinary Geographer specialising in fluvial geomorphology. She is the Stroud Water Research Center leading principal investigator for the research team and contributes to the hydrological, biological and geomorphological research components.
E: mdaniels@stroudcenter.org

Dr David Haukos
Dr David Haukos is a wildlife ecologist concentrating on the relationships among landscape composition, population demography, and animal space use.
E: dhaukos@ksu.edu

Dr Aleksey Sheshukov
Dr Aleksey Sheshukov is a quantitative hydrologist specialising in evaluating the impacts of climate variability and land-use change on watershed water-quality and surface hydrology with computer models.
E: ashesh@ksu.edu

Dr Joe Aistrup
Dr Joe Aistrup is a political scientist focused on the intersection between water policy and communities in water abundant and water scarce environments.
E: jaistrup@auburn.edu

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THE ROLE OF POLICIES IN MANAGING SCARCE WATER RESOURCES

Water scarcity and perverse policies may have severe effects on the environment, affecting society both directly and indirectly. A team from the Agrifood Research and Technology Center (CITA), the University of Zaragoza, the International Institute for Applied Systems Analysis, and the University of California Riverside has carried out extensive research exploring the various components of the Jucar River Basin's water ecosystem, as well as factors affecting its performance.

Growing Pressure on Water Resources

Because of climate change and the continuous growth of the world's population, pressure on water resources has been increasing exponentially over the past century, with severe repercussions in wealthy and developing countries alike. This mounting pressure on water extraction poses two main issues: water scarcity and water pollution.

Water scarcity can seriously compromise agriculture, environment, industry, energy, and many other aspects of society. Additionally, increased water pollution can result in several river tracts and aquifers no longer being able to sustain water ecosystems and hindering human activities.

Over the past few decades, water scarcity has become a widespread problem, affecting most arid and semiarid regions, including the basins of the Ganges, Indus, Yangtze, Tigris, Euphrates, Nile, and several other rivers. Therefore, investigating water policies that might be detrimental or beneficial to society is of critical importance, as this could help identify the most effective ways of managing water resources.

The Jucar River Basin

A group of researchers from the Agrifood Research and Technology Center (CITA), the University of Zaragoza, the International Institute for Applied Systems Analysis (IIASA), and the University of California Riverside has been conducting extensive research exploring the impact of policies and politics in managing scarce water resources, with a particular focus on the Jucar River Basin in Spain.

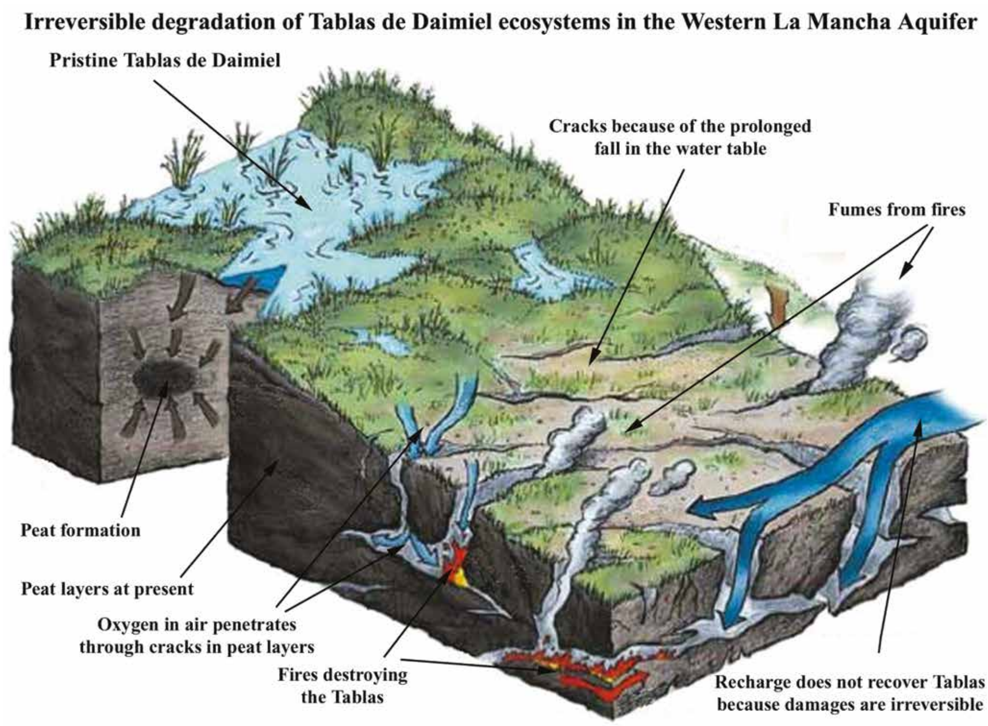
The team includes Dr Jose Albiac from CITA and Dr Encarna Esteban from the University of Zaragoza, as well as Dr Taher Kahil from IIASA and Dr Ariel Dinar from the University of California, Riverside. 'Our work on the Jucar River Basin in Spain focuses on the various components of the river basin ecosystems such as groundwater, wetlands and irrigated agriculture,' says Dr Albiac.

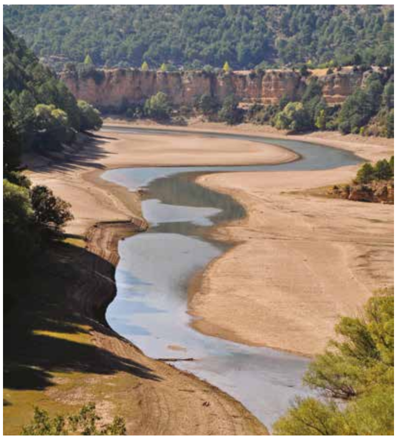
The researchers developed several hydro-economic modelling frameworks and used them to estimate the impacts of different policies on the performance of river basin ecosystems. 'Our work contains the main components that are essential to water management, including economic optimisation and water allocation, interaction

between surface and groundwater resources, the role of groundwater-dependent ecosystems, regional value of cooperation, the role of institutional arrangements with emphasis on extreme scarcity situations, and perception about policy interventions by various stakeholders,' explains Dr Kahil.

The Role of Policy in Water Management

The theory of exhaustible resources, such as groundwater, is an important aspect of economics that addresses the difficulties in establishing property rights for shared resources. Groundwater is a common pool resource accessed by several different parties, so extractions by one user automatically reduce the water available to others. Most users believe that the competitors will not conserve water for the future and hence do not make any effort to protect the water stock, ultimately causing a





market failure that requires regulatory interventions.

Past studies comparing strategies of managing aquifers found that different policy interventions had similar outcomes. Several researchers argued that policy regulation does not effectively improve social welfare, thus questioning the role of public policy and its value in sustaining resource use over time.

In two research studies that challenged this argument (Esteban and Albiac, 2011, 2012), Drs Esteban and Albiac analysed the water management strategies employed in two aquifers, the Eastern and Western La Mancha aquifers, which are connected to the Jucar River Basin (Eastern) and to the Guadiana River Basin (Western). This case is of particular interest due to the stark contrast between water management in the Eastern and Western La Mancha aquifers. While the Eastern La Mancha is almost sustainable, the Western aquifer is being grossly mismanaged, raising interesting questions about the role of policy in these markedly different observations.

The researchers simulated three different management regimes: free market, partial cooperation, and full cooperation. Their findings suggest that policies did have an effect on water management – with policies encouraging full cooperation and collective efforts, such as the ones implemented in the Eastern La Mancha aquifer, being far more beneficial compared to the free market management that is present in the Western region.

A further series of studies by Drs Esteban and Dinar assessed the conjunctive management of groundwater both in theory and applied to the Jucar River Basin (Esteban and Dinar, 2013, 2016). The researchers demonstrated that policy interventions can help sustain the aquifer when the environmental ecosystem is considered and has positive value and significant value to society.

Applying their theoretical model to the Western la Mancha aquifer, they also found that packaging and sequencing of a set of policy interventions is potentially far more effective than single policies in achieving sustainable groundwater management. This particular model of combining policy interventions includes policies such as water taxes and water quotas. Using their economic model, the team found that a sequential package intervention of quotas and taxes results in more efficient water management than when these policies are applied individually.

Dr Dinar and Dr Esteban also developed a game theoretical framework (a mathematical model used in economics to analyse strategic interactions between actors in a given market), to assess the value of cooperation between different stakeholders in the Eastern La Mancha aquifer (Esteban and Dinar, 2013). Their findings suggest that uncontrolled extractions and environmental factors interact in affecting the likelihood of cooperation among water users in the area. 'This finding supports the arguments made by the team, which supports policy intervention when negative environmental externality does exist,' says Dr Esteban.

Political Aspects of Water Management

The existence of water users with opposing interests and varying political power makes implementing water policies in the Jucar River Basin extremely difficult. Therefore, the researchers collected and examined the divergent perceptions of different interest groups in the region on the implementation of water scarcity interventions, as well as the extent of their involvement with water agencies. They sent out questionnaires to upstream irrigators in the Eastern la Mancha Aquifer, downstream irrigators in the lower Jucar River Basin, and urban users residing in the Valencia region (Esteban *et al*., 2018).

By analysing the retrieved information, the team found that there were significant differences among these interest groups' preferred measures of addressing water scarcity, which varied according to the size of the group, their location in the basin, and other characteristics. These findings have several implications that could inform policy making in the future. For instance, they suggest that smaller groups with sizable landholdings are more politically organised than larger groups with smaller landholdings. In addition, more organised groups were found to be more proactive and involved with authorities in the area. Furthermore, while the researchers observed sizeable differences in different groups' perceptions of the efficiency and fairness of water policies, some opinions appeared to be shared by many.

Policy Interventions Under Different Scarcity Levels

In the years to come, climate change is expected to exacerbate water scarcity and increase the occurrence of droughts, especially in arid and semiarid regions of the world. To better understand water management during droughts, Drs Kahil, Albiac and Dinar examined various policy interventions under different water scarcity scenarios, using the Jucar River Basin as an example (Kahil *et al*., 2015, 2016).

They developed an integrated hydro-economic model that links hydrological, economic, and environmental elements within the context of policies for the management of water scarcity. They then used it to carry out a direct comparison of water markets, water pricing and institutional cooperation policies in the Jucar River Basin, based on their economic, environmental and equity outcomes.

Their results highlighted both institutional and water market policies as highly performing instruments to limit the adverse economic consequences of droughts, each with almost the same private benefits. The same study also found water market interventions to have worrying environmental effects and suggested that water pricing is a poor policy option, both in terms of private and environmental benefits and in terms of social equity.

In contrast, environmental water market policies, under which the basin authority acquires water for the Albufera wetland (the main aquatic ecosystem in the Jucar River Basin, and the second most important wetland in Spain), was identified as an appealing option because it ensures private benefits of markets, distributes drought damages more evenly, and offers greater protection for the water ecosystem.

The team of researchers also developed a cooperative game theory framework that can be used to analyse water management policies that address scarcity and drought (Kahil *et al*., 2016). Applying this framework to the Jucar Basin, they found clear evidence that achieving cooperation between different stakeholders can reduce significantly the costs of drought damage. When scarcity is particularly high, however, this cooperation might have to be regulated by public agencies, in order to protect the ecosystems and maintain sustainable level of economic benefits.

Towards More Effective Water Management

The research carried out by Drs Albiac, Dinar, Esteban and Kahil clearly demonstrates the benefits of interventions that encourage cooperation between different stakeholders in regions affected by water scarcity. Their work is an important contribution to the area of economics that focuses on water management, and has helped identify interventions and factors that are unhelpful or not beneficial in the Jucar River Basin.

As the world population keeps growing and the climate continues to change, attaining a deeper understanding of how water resources can be managed more effectively is of utmost importance and could have immeasurable benefits for society. In future, the results collected by the team could inform policymakers, leading to the development of more effective interventions that encourage cooperation and consider the differences between distinct interest groups. The researchers are now planning to expand the scope of their research to explore other areas of water management.

'Our work on the Jucar River Basin mainly includes water quantity aspects, principally because this is the limiting factor in that basin,' says Dr Albiac. 'However, water quality – mainly nutrient pollution and soil salinity – are limiting factors in many other river basins.' To take a closer look at these factors, the team will be studying other water ecosystems in Spain, with similar characteristics to river basins in other parts of the world.

Meet the researchers

Dr Jose Albiac

Dr Jose Albiac is a researcher at the Agrifood Research and Technology Center (CITA - Government of Aragon) and a professor at the University of Zaragoza, Spain. He attained a BSc in Economics from the University of Zaragoza, followed by an MSc and a PhD in Agricultural Economics from the University of Illinois, USA. Dr Albiac's research focuses on environmental and natural resource economics, environmental and agricultural policies, water management, irrigation, groundwater, ecosystems services and protection, nonpoint pollution, water scarcity, droughts, and climate change.

E: maella@unizar.es

Dr Ariel Dinar

Ariel Dinar is a distinguished professor of Environmental Economics and Policy at the University of California, Riverside (UCR). He holds a BSc, MSc and PhD in Agricultural Economics from the Hebrew University of Jerusalem in Israel. His research focuses on water economics and management at different levels, including regional and international. Dr Dinar has countless publications to his name, including journal articles, articles in policy outlets, and books. Before joining UCR in in 2008, he spent 15 years at the World Bank in Washington DC, working within the policy and research departments on water policies for developing countries, as well as on climate change impact and adaptation.

E: adinar@ucr.edu

Dr Encarna Esteban

Dr Encarna Esteban is an associate professor at the Department of Economic Analysis of the University of Zaragoza, in Spain. She holds a PhD and BSc in Economics from the University of Zaragoza, as well as a MSc in Agricultural and Resource Economics from the University of Connecticut, USA. Her research primarily focuses on studying water bodies, analysing both their quantitative and qualitative properties, as well as investigating ecosystem behaviour, ecosystem services, and political economy applied to natural resources. Dr Esteban's work is based on environmental economics, natural resources, mathematical optimisation, simulation, and modelling applied to water problems.

E: encarnae@unizar.es

Dr Taher Kahil

Dr Taher Kahil is a research scholar at the International Institute for Applied Systems Analysis (IIASA), in Austria. He holds a BSc in Agricultural Economics, an MSc in Environmental Management, and a PhD in Economics from the University of Zaragoza. His PhD dissertation focused on the development and use of a hydro-economic model of Spanish basins and on the application of cooperative game theory to water resources management. Dr Kahil's research interests include integrated water resources modelling and optimization, water economics and policy, the assessment of climate change impacts, and policies in the agriculture and water sectors.

E: kahil@iiasa.ac.at

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KEY COLLABORATORS

Elena Calvo, University of Zaragoza
Lorenzo Avella, Polytechnical University of Valencia
Marta Garcia-Molla, Polytechnical University of Valencia

Facultad de Ciencias Sociales y Humanas - Teruel Universidad Zaragoza
International Institute for Applied Systems Analysis IIASA www.iiasa.ac.at
cita
GOBIERNO DE ARAGON
UCR School of Public Policy

HOW CAN AGRICULTURE IN THE COLORADO RIVER BASIN BEST ADDRESS PRESSURES ON ITS WATER?

Water from the Colorado River is critical for agriculture, people and the environment. As populations burgeon and environmental flows are in jeopardy, many see agriculture as the 'go to' source to meet shortages. A group of researchers at Colorado State University has been working with Colorado River Basin agricultural producers and water managers to address this question: Can agriculture cooperate with other sectors to meet water shortages without compromising their ability to produce food and fiber and maintain the viability of rural amenities we all enjoy?

The Colorado River is a major source of water for seven western US states and Mexico, with more than 35 million people dependent on this over-appropriated resource. Urban growth, climate change, and increased recognition of environmental needs all play a role in the projected shortage of Colorado River water in the near future. Long-running drought has significantly lowered the levels of Lakes Mead and Powell – reservoirs key to interstate river water management and hydropower needs.

Diversions of water from the river are greater for agriculture than any other use, so agriculture is targeted for conservation, even though agriculture itself may need more water in the future to meet growing global food demands.

The US Bureau of Reclamation undertook a series of efforts to study the question of water shortages in the Colorado River Basin (CRB) and what might be done to address it. A recommendation of their Basin Study was that one million acre-feet of water currently being used in agriculture could be freed up to meet growing municipal and environmental demands. Many doubt whether that goal is feasible.

The Complexity of the Term 'Ag Water Conservation'

The term 'Ag Water Conservation' has been used by many outside agriculture, and is often seen as a panacea. 'If farmers would conserve water, there would be plenty for other uses,' is a common call. There are decisions farmers can make, and practices they can employ, to use less water. But for those decisions and practices to result in water that can be used for other purposes – such as leaving water in the stream for fish or transferring water to cities – a complex maze of issues must be addressed. And the trade-offs could likely include reduced crop production and loss of wetlands initially created by agricultural practices.

Irrigation efficiency improvements are an important tool with multiple benefits, but to determine the potential role of irrigation efficiency improvements in conserving agricultural water, one must delve into such complexities as 'crop consumptive use' and 'return flows' – the intricacies of which confound not only the public but sometimes agricultural irrigators themselves.The phrase 'use it or lose it' has been used and misused by many, adding to the confusion.

The Colorado River Basin

funding provided by: USDA United States Department of Agriculture National Institute of Food and Agriculture

The institutional and legal framework that governs how water can be applied under the prior appropriation doctrine has worked in the CRB since the late 1800s as a means of fairly distributing water for agricultural and later, urban diversions. It's a system based on private use, however, and the needs of the environment have only recently been integrated into the framework and are therefore usually junior. Whether some water currently being used in agriculture might be temporarily transferred, through fair compensation, to meet urban and environmental needs while preserving our food supply, the wildlife habitat and rural ambiance agriculture provides, is a difficult and complex question. It's the question a group of researchers at Colorado State University set out to explore.

Two CSU Projects for the USDA

For the past seven years, in two USDA funded projects, the Colorado Water Institute at Colorado State University has engaged with CRB agricultural producers and those who manage their water to explore how agriculture might best respond to pressures to free up water to help meet increasing demands for Colorado River water.

For the first project, CSU was advised by a team of water research institutes from the land grant universities in the CRB states – Arizona, California, Colorado, Nevada, New Mexico, Wyoming, and Utah. Extensive interviews and a survey provided insights into what farmers, ranchers and their Ag water managers consider to be pressures and how they're dealing with them.

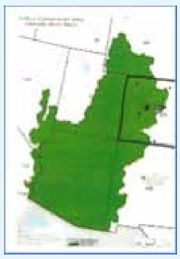
Building on the first project, CSU's second USDA project drilled into the question: 'What do CRB Ag producers and water managers see as strategies they might take to free up Ag water to meet projected water shortages while securing irrigated agriculture into the future (http://crbagwater.colostate.edu/)?

Addressing the Question from Agriculture's Perspective

Worldwide food demand is projected to increase greatly. As a land grant institution, CSU approached the question from the agricultural viewpoint, recognising the need for the sector to face the demands for water in ways that position them to make water for agriculture more secure rather than more vulnerable. They believe that water security is bolstered when agriculture aims to be part of a complex solution instead of taking a staunch 'don't try to change us – hands off our water' attitude. The research team recognises that agriculture is more than just an economical venture and set out to tackle the myths about irrigated agriculture in the CRB.

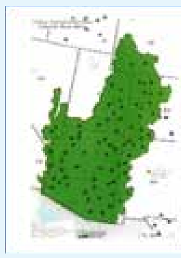
Demonstration of Irrigation Efficiency Improvements

CSU researchers worked with No Chico Brush, a grassroots farmer group, to install and test a variety of irrigation management and equipment improvements. Their motivation is not to free up water for use by cities. Instead they want to put their water to its very best use to maximise its productivity for crop production/profit and to stretch it further in times of drought. They believe that by showing they are using their water as efficiently as possible, they can avoid future political pressure to sell their water for other uses (http://crbagwater.colostate.edu/objective1.shtml).



80+ Cases of Ag 'Water Sharing' Compiled

The team combed the literature to find more than 80 cases in the CRB and beyond where agricultural water has been changed in a temporary way to meet multiple uses. These cases offer examples of success as well as occasional failure, illuminating factors at play that influence why and how such projects were undertaken (http://www.cwi.colostate.edu/media/publications/sr/27.pdf and http://crbagwater.colostate.edu/files/Case%20Studies%20for%20Website%202%2024%2016.pdf).



CRB Ag Water Conservation Clearinghouse

The team created a CRB Ag Water Conservation Clearinghouse (http://CRBawcc.colostate.edu/), which compiles information regarding agricultural water conservation in the CRB to help build collaborative relationships between and among agencies, and to offer detailed information and technical expertise on the management, policies, and laws surrounding Ag water conservation in the basin.

Sociological Investigation of Ag 'Water Sharing' for Multiple Benefit

CSU sociologists set out to document and analyse the legal, economic, and social barriers to conserve agricultural irrigation water in the CRB. The researchers conducted an extensive literature review and engaged in more than 50 in-depth interviews with producers involved in six cases of multi-stakeholder collaboration to provide agricultural water for multiple other purposes. The cases include:

- **Temporary leasing of agricultural water for municipal use in the lower Arkansas valley of Colorado**
- **A major rotational fallowing program in California to provide drinking water**
- **A pilot project in Arizona's Yuma County to generate saved 'system water' to offset the effects of drought on Lake Mead**
- **Managing river flows to benefit endangered fish species while improving agricultural irrigation results in western Colorado**
- **Employing 'split-season' irrigation agreements that pay ranchers to reduce their water use late in the season to keep water instream for fish**
- **Diversion structure improvements to improve irrigation management and stream flows on the tributary Verde River in Arizona**

The six in-depth case studies of multi-stakeholder collaboration for agricultural water conservation show that under the right structural and social conditions, such collaboration can prioritise agricultural security while temporarily freeing up water in ways that benefit multiple parties. Enabling structural conditions include: water's movement across geographic and social landscapes of diverse water uses in ways that simplify management of return flow injuries to third parties; allow shepherding of conserved water to intended beneficiaries; and permit effective coordination of the timing and intensity of water delivery for multiples uses. They include legal frameworks that allow for and incentivise water conservation and create safe administrative spaces for experimentation and innovation. Similarly, enabling local social and political conditions are needed that encourage diverse water users to come to the negotiation table and remain there for individual and community benefit. Collaborative water conservation also requires agricultural production systems, including soils, crop types, technology and markets, that allow farmers to derive more benefits from water conservation than risks to their livelihoods.

Dialogue to Strategize Multi-Benefit Approaches

In two major workshops, one in the lower CRB and one in the upper CRB, researchers brought together those interested in or concerned about agricultural 'water sharing' to discuss alternatives to permanent transfer of water from agriculture to meet other demands. These workshops were based on an extensive synthesis of alternatives to permanent fallowing research (http://cwi.colostate.edu/media/publications/cr/232.pdf). Several methods were discussed that are seen to have potential, including a pilot program to free up 'system water' for Lake Mead, if the problem of how to shepherd agricultural water from its origin could be solved (http://cwi.colostate.edu/media/files/shepherding/2017-11-14_Workshop-Report.pdf).

Within the state of Colorado, more than a dozen other workshops and meetings yielded significant insights about attitudes surrounding Ag water conservation. A better understanding of these attitudes and positions can be instrumental in improving collaborative efforts (http://www.cwi.colostate.edu/media/publications/sr/31.pdf).

The team engaged with the State of Colorado's Division of Water Resources to convene influential water lawyers, agricultural and conservation groups, and others to investigate the concept of 'use it or lose it', believed by many to be a major stumbling block to acceptance of Ag water conservation. Analysis of pertinent statutes in state law led to publication that is spurring needed dialogue among Ag producers and others (http://www.cwi.colostate.edu/media/publications/sr/25.pdf).

Engagement of Students in Dialogue about Water/Water Conflict

In a variety of settings, the team worked with students to share project findings and to engage them in dialogue about multi-stakeholder collaboration.

- Three groups of agricultural and natural resources students at CSU participated in facilitated dialogue to help them understand and bridge differences in values, leading to collaboration instead of conflict.
- Five graduate students received insights from facilitators and mediators active in the work of water stakeholder collaboration, and practiced skills learned.
- Eight Latino CSU students were chosen for an inaugural program – CSU Water Sustainability Fellows – designed to increase interest in water issues from underrepresented populations.
- Five CSU Water Sustainability Fellows were granted paid summer internships to work with six low-income high school students of color to learn about water issues related to the expansion of the national western stock show complex in Denver. Together, these eleven students planned a Denver Youth Water Summit.

Lessons Learned

- Many technical, legal and social obstacles to Ag water conservation can be overcome if safe space is created for ditch companies and irrigation districts to work and experiment with those from other sectors to lead to mutually beneficial outcomes.

- CRB water governance system is not set in concrete. Changes can be made and workarounds are possible at the local scale. The technical and social/economic sides ought to be pursued concurrently. Each ditch company and irrigation district is unique and there will not be a single approach that works everywhere.

- Getting Ag producers or groups of ditch companies to work together can be difficult, but it's a crucial first step. Various approaches tried in different places have yielded insights that can be instructional in showing what has and has not worked under certain circumstances. In many cases, it's not clear what's being asked from Ag. Clarifying that will lead to greater cooperation and less resistance from agriculture.

- Irrigation efficiency and Ag water conservation are not the same, yet the terms are often used interchangeably. Efficiency improvements may or may not contribute to river flows. True conservation usually means a reduction of crop consumptive use, which comes with a yield penalty and loss of revenue in many cases. Consistent use of proper terminology and understanding of the complexity is critical if we want to make the changes needed to meet specific objectives and achieve desired outcomes.

- What's needed is accurate and uniform quantification of diversions, crop ET, irrigated acres, and return flows. This can be tackled with current technology but most farmers at this point don't see a benefit for consistent volumetric measurement and may even oppose it.

- Switching to other crops requiring less water is often held up as a solution, but data and studies to date do not convince producers. Economics, markets, climate and water availability largely determine crop and livestock choices, as well as irrigation system type. Other sectors and the public need to realise the costs and trade-offs required for crop switching to be realistic.

- The current Ag economy in the upper basin states of the CRB cannot absorb the costs of system improvements to be more efficient. Financial incentives do not exist for forage crop producers to become more efficient without significant external incentives.

- Ag is not just economics or purely business; there are social, cultural, generational complexities at play. In many cases, farmers have rational reasons to wait before they make changes in their operations.

- Small projects can be successful locally, but they alone are not going to bring the system into balance. To make a significant difference in the basin scale water balance, coordinated system-wide actions at the head gate are necessary to reduce diversions while maintaining return flows. This will require significant public investment and likely some market-based solutions.

funding provided by: USDA United States Department of Agriculture National Institute of Food and Agriculture

WHAT IS NEEDED NOW

Quantification
Tackle the science, data and modelling needs to quantify consumptive use and return flows on a parcel basis that can be spatially scaled through remote sensing.

Irrigation Efficiency Measures
Take a close look at the irrigation efficiency improvements recommended under the Regional Conservation Partnership Program of the USDA's Natural Resources Conservation Service. To what extent will irrigation efficiency improvements affect return flows, delivery patterns, junior water rights holders, and the ecosystem services of the impact areas?

Markets
What market-based conditions could incent farmers to conserve, reduce or forego diversions, and engage in short or long-term transfers? Are water market solutions (temporary and permanent transfers) more cost-effective than spending funding on irrigation system improvements (looking at long-term agricultural and food security?)

Shepherding
The problem of shepherding conserved water from the point of conservation to an intended use elsewhere (up or down) on the stream is a major obstacle. This requires consideration of hydrological, legal and social-organisational factors.

Legal / Institutional
Investigate the challenges and possibilities of legally and politically institutionalising the conservation of water as a formal beneficial use by a user and therefore, protecting the conserving water user's existing water right.

Closing

Virtually all those using water for agriculture in the CRB are involved in some degree of conflict, much of which is related to water leaving agriculture for urban uses. Another large part of the conflict is disagreement over the permitting of new or enlarged storage projects seen by most agricultural water users as critical for wise use of resources and seen by some environmental groups as detrimental to natural habitats.

Some of the wild cards include water rights held by energy developers who are not yet calling on those rights, unquantified tribal claims amounting to as much as 2 million-acre feet of Colorado River water, and the vulnerability of large cities like Denver who have relatively junior rights to Colorado River water and could be called out if the lower basin states do not get the water to which they are entitled.

Solutions to both long and short-term water shortage emergencies on the already over-appropriated Colorado River need to be devised in close consultation with irrigators before the inevitable drought or other shortage creates a crisis.

The dilemma of how to reconcile or manage competing demands for Colorado River water will never go away. Improving communication and relationships between agricultural, urban and environmental stakeholders will likely be the best tool we can use and improve going forward.

EMPOWERING HIGH DESERT COMMUNITIES BUILT FOR CHANGE

The acequia communities of the southwestern United States build on traditional practices and knowledge to sustain community-managed irrigation systems. Interdisciplinary researchers from New Mexico State University, the University of New Mexico, Sandia National Laboratories, and the New Mexico Institute of Mining and Technology worked closely with these communities to understand their resilience and adaptive capacity and to promote wellbeing in the face of emerging threats.

In the arid southwestern United States, communities center on a valuable resource: water. In the late 16th century, Spanish colonists transformed the desert landscape by installing a network of irrigation canals and ditches, known as acequias (pronounced *ah-say-key-uh*). These channels are typically unlined with water naturally fed to them by gravity from adjacent streams and rivers. Local communities, using traditional knowledge passed down through generations, manage the acequias together and collectively share the resources.

Typically, acequias are spread throughout the narrow alluvial floodplains adjacent to rivers and streams. When acequias thrive, so do other ecological and hydrological functions including an enhanced habitat to support multiple aquatic and terrestrial species typical of riparian areas. In that sense, acequia irrigation systems mimic seasonal streams and pools of water characteristic of natural floodplain systems.

Acequias provide communities and associated regions with valuable ecosystem services (benefits individuals and communities gain from well-functioning ecosystems). Such ecosystem services include diluting contaminants in the groundwater supply, including nitrates, and contributing to riparian habitat. However, changes to the region are imminent, and various threats to these historic landscapes have recently emerged.

Many threats that scientists have identified as menaces to other ecosystems around the globe are also shifting the resources available within acequia communities. Worldwide, shifts in land usage such as the urbanisation occurring in some rural communities are threatening traditional agricultural systems. The acequia communities' land use is also changing from growing crops and fruit trees to constructing homes and commercial buildings. These changes threaten the sustainability of these traditional irrigation communities and some of the ecological and hydrological function benefits provided.

To address these concerns, a team of interdisciplinary researchers

from universities and national labs worked with the New Mexico Acequia Association and several acequia communities in the state's northern region. They employed complex mathematical models to understand and generate resilience within these long-standing communities.

Redefining Disciplines

The project, which was funded by a $1.4 million National Science Foundation grant beginning in 2010, aimed to understand how the socioeconomics, culture, hydrology and ecosystems associated with acequias are linked and to characterise their sensitivity to

possible ‘tipping points’ that may affect the survival of these systems in northern New Mexico.

The collaborative team included researchers from New Mexico State University, the University of New Mexico, Sandia National Laboratories and the New Mexico Institute of Mining and Technology, with diverse expertise across disciplines. The team collaborated extensively with local educators and acequia leaders, as well as Chilean researchers who were conducting a comparative study on similar community-managed irrigation systems in their region.

Using long-term historical datasets, future scenarios, surveys completed by local acequia community members and hydrology data collected by their team, the researchers aimed to understand the complex relationships that allow acequia systems to remain resilient in the face of change. In particular, they studied how acequias affect surface water and groundwater. They also analyzed how wildlife habitats and cattle grazing areas connect with local wetlands, forests and grasslands to maintain healthy ecosystems. Most importantly, they identified potential ‘tipping points’ using mathematical models that simulate the effects of different future scenarios. These insights can help the communities to remain resilient, as they have for centuries, under various pressures.

The team prioritised the dissemination of their research goals by reaching a broad audience of educators, policy makers and community members through hands-on involvement. The project actively recruited rural acequia community members and asked them to define resilience in their community and prioritise their needs.

Working with the University of New Mexico Maxwell Museum of Anthropology, the team also helped to create an exhibit entitled ‘El Agua es Vida: Acequias in New Mexico’ to educate the public on these communities. In addition, the researchers engaged with a scientific audience by hosting a Global Perspectives Workshop in 2013 on ‘Acequias and the Future of Resilience in Global Perspective’. They have also published multiple scientific papers on this work and are currently working to publish a book summarising their findings. Information has been made available to policy makers with the aim to guide policy toward decisions that help to maintain flourishing acequia communities.

A Water Savings Account

Acequias may help to counteract the negative effects of a changing climate on regional hydrology. One major effect of a warming planet in the southwestern United States appears to be less snowpack. This snowpack is also melting earlier in the year than before.

By measuring water balance components and using hydrologic models, the research team found that acequia irrigation systems can help recharge the shallow aquifer for temporary storage underground. This stored water is released into the river later in the year, helping to maintain stream flow for downstream users and to maintain environmental flows for stream and riparian species habitat. Seepage from acequia systems during the irrigation season also helps to improve groundwater quality by diluting nutrient concentrations from residential leaching.

Overall, it seems that acequia systems in northern New Mexico may help to save water in the Rio Grande Basin by reducing direct evaporative losses through storing water underground during the summer. This is in contrast to open water bodies such as reservoirs or lakes, which are known to lose large amounts of water to evaporation every year.

Traditions May Be the Solution

The close-knit, rural acequia communities of northern New Mexico are particularly vulnerable to stress from a growing population. As the population increases, the composition of the community shifts, economic hardship persists, and pressure to develop increases. In addition, projections for climate change in the region forecast water scarcity in an area where water is already a strained resource and an increase in the intensity and frequency of severe weather events, such as droughts and floods.

Team members adopted a unique method to understand how these acequia communities will adapt to change – using a 'snowball' approach to survey the local population. By working with local leaders, introductions were facilitated between interviewers and community members. This engendered a greater level of comfort and acceptance, allowing the team to survey a larger portion of the population and to elicit their underlying sentiments toward change. The researchers aimed to understand the community perception of current preparedness and the capacity to adapt to change. They also identified several steps that the community can take to enhance their preparedness and overall resilience.

Over 800 acequia communities exist in New Mexico, which are built upon the idea of 'repartimiento' – the sharing of water and the sharing of the responsibility for the management of this resource. As these communities grow with the influx of newcomers from other areas, their new neighbors do not necessarily share native acequia residents' attachment to water.

The team's survey was able to capture the communities' ideals and highlighted the respondents' prioritisation in maintaining the ditch infrastructure, protecting the community waters from outside diversions, building community spirit of cooperation, and maintaining a self-governing organisation. In addition, land ownership and family connections to the land, water and community were shared sentiments when asked which characteristics helped the participants to adjust to threats in the past. To combat drought, the communities identified soil improvement to reduce evaporation as a potentially promising strategy in the future.

There is also a growing sentiment that public awareness of acequia knowledge and traditions is essential to the survival of this community in the future. By providing hands-on training, education, and practical demonstrations of traditional knowledge, local communities may be able to protect the community waters in the face of change.

Farming for the Future

Using historical datasets of livestock numbers, drought and hay production, coupled with surveys of farmers and ranchers, the research team was able to understand how water allocation influences the economics of livestock in acequia agriculture. Many acequia farmers raise livestock and the majority of these farmers believe that livestock provide better financial security than crops. However, the researchers found that county hay production directly relates to yearly livestock numbers, which is highly dependent on water reserves. In particular, the ability to acquire winter hay appears to limit the size of herds and therefore the farmer's yearly profit.

To make matters more complicated, acequia communities historically grazed their livestock on common lands, until the

early 20th century, when their lands were placed under the jurisdiction of the United States Forest Service and Department of the Interior. This change in land policy fragmented the traditional land management connections of the entire upland-valley continuum.

Therefore, today many who still practice acequia farming must lease public grazing lands in the uplands and controversy over land tenure rights still persists. Livestock feed practices changed to rely more on irrigated hay that is now grown in the valleys. Even though the upland-valley connections were affected by changes in land usage and policy, the physical connections between the irrigated valley and contributing watershed still exist due to the role that acequias play in redistributing snowmelt runoff through the agricultural system. Data derived from this study was used in simulation models to test if these traditional farming practices are resilient to expected changes in climate and social factors.

Simulating Success

Using cutting-edge mathematical models, the research team was able to ask a question critical to the health of this community: what will happen in the future? The project aimed to understand whether acequias will be resilient with future changes and what they can do to promote a sustainable future. These mathematical models bring together four main disciplines in search of answers: hydrology, ecology, economics, and sociology.

The team found that when water supplies decrease, the community must rely on local knowledge of the water system, a deep-rooted ethic of water sharing and other forms of social capital, while also being willing to modify traditional water management practices. Among livestock producers, some were not able to stay in the sheep ranching business when labor became less available, wool and lamb prices dropped in the late 1950s and early 1960s, and sheep grazing permits were no longer issued. Many shifted to cattle and/or continued producing hay on their irrigated land for winter cattle feed or for sale.

By continuing to irrigate using traditional methods, water recharges the groundwater supply for use later in the year, supports biodiversity in local ecosystems, and ameliorates the effects of climate change by prolonging stream flow. The team used their models to evaluate the impact of the acequia community's social structure in governing its responses to water availability stresses posed by climate change. Although stream flows were found to decrease on average and shift to earlier in the season, adaptive measures of adjusting crop selection allowed for greater production of higher value crops and fewer people leaving the acequia. However, the team found that economic benefits were lost if downstream water pressures increased.

Even with significant reductions in agricultural profitability, feedbacks associated with community cohesion buffered the community's population and land parcel sizes from more detrimental impacts, indicating the community's resilience under natural and social stresses. Overall, the team's studies highlighted the importance of mutualism within the community as a key feature of resilience, and customary practices of sharing both the water resource and management responsibility, as the acequia community has done for generations.

The acequias project demonstrates the ability for a multi-disciplinary team to work together with local communities to prioritise future health in a changing climate. By detailing concrete solutions and actively working to disseminate research results to the community and policy makers, the team continues to educate stakeholders on the importance of acequia systems for future use.

Meet the researchers

Dr Alexander 'Sam' Fernald
Dr Fernald is the project's Principal Investigator. He is a Professor of Watershed Management in the Department of Animal and Range Sciences at New Mexico State University.
E: afernald@nmsu.edu

Dr Kenneth Boykin
Dr Boykin is a Research Associate Professor and Ecologist with the Center for Applied Spatial Ecology in the Department of Fish, Wildlife, and Conservation Ecology at New Mexico State University. He is also the Director of New MexicoView, a consortium of members and institutions that are committed to the advancement and dissemination of remote sensing technology in New Mexico.
E: kboykin@nmsu.edu

Dr Andres Cibils
Dr Cibils is a Professor of Range Science in the Department of Animal and Range Sciences at New Mexico State University. He collaborates with researchers in Argentina, Chile, Mali, Mexico, Mongolia, Scotland, and Uruguay, and has volunteered in farming communities of Central America and West Africa.
E: acibils@nmsu.edu

Mr Moises Gonzales
Mr. Gonzalez is an Associate Professor of Community and Regional Planning in the School of Architecture and Planning at the University of New Mexico.
E: mgonzo1@unm.edu

Dr Steven Guldan
Dr Guldan is a Professor of Agronomy, Department of Plant and Environmental Sciences, and Superintendent of the Alcalde Sustainable Agriculture Science Center; New Mexico State University.
E: sguldan@nmsu.edu

Dr Brian Hurd
Dr Hurd is a Professor of Agricultural Economics and Agribusiness at New Mexico State University.
E: bhurd@nmsu.edu

Dr Carlos Ochoa
Dr Ochoa is an Assistant Professor of Watershed-Riparian Systems in the Department of Animal and Rangeland Sciences at Oregon State University.
E: Carlos.Ochoa@oregonstate.edu

Dr José Rivera
Dr Rivera is a Professor Emeritus at the School of Architecture and Planning and serves on the Research Staff of the Center for Regional Studies, University of New Mexico.
E: jrivera@unm.edu

Dr Sylvia Rodríguez
Dr Rodríguez is a Professor Emerita in the Department of Anthropology and former Director of the Ortiz Center for Intercultural Studies at the University of New Mexico.
E: sylrodri@unm.edu

Dr Vincent Tidwell
Dr Tidwell is a Distinguished Member of Technical Staff at Sandia National Laboratories.
E: vctidwe@sandia.gov

Dr John Wilson
Dr Wilson is a Professor of Hydrology and Senior Research Hydrologist (Retired) at the New Mexico Institute of Mining and Technology.

NM STATE

Sandia National Laboratories

PROJECT WEBSITE

http://wcrg.nmsu.edu/cnhacequia/

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IMPROVED DROUGHT EARLY WARNING SCIENCE HELPS SAVE LIVES AND LIVELIHOODS IN AFRICA

Bringing together multidisciplinary scientists and food security analysts from UC Santa Barbara, Africa and Central America, the Climate Hazards Group develops datasets, tools and forecasts that help guide effective disaster responses and long-term development plans in food insecure countries. Working closely with partners in the US Geological Survey, NASA, and the Famine Early Warning Systems Network, the team uses climate and hydrologic models, satellite-based earth observations, and socio-economic data sets to predict and monitor droughts and food shortages among the world's most vulnerable populations, supporting critical planning and timely humanitarian assistance that save lives and livelihoods.

When climate variability and shifting climatic trends converge to produce severe droughts, fragile food insecure populations may rapidly face severe food crises as supplies drop, prices rise and household incomes decline. In vulnerable areas, these unanticipated climate shocks may devastate herds and harvests threatening local food stocks. Unfortunately, the number of very hungry people has been growing at an alarming rate over the past few decades, with more than 76 million people experiencing life-threatening conditions in 2017 and 2018.

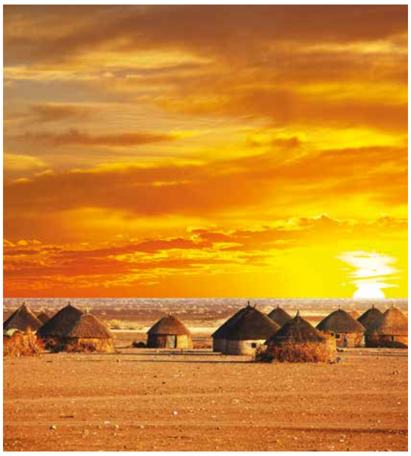
This recent increase in food insecurity has been most apparent in less developed regions of the world, especially in Africa, where many people are already vulnerable to the impacts of droughts and floods. Using traditional monitoring and forecasting methods, it is difficult to predict when these vulnerable regions will be most in need of humanitarian aid with adequate advance notice.

To address this problem, the Climate Hazards Group (CHG) works with US, African and Latin American partners to develop and deploy improved earth observations, forecasts, and capacity building decision support tools.

Water is Key

In 1985, the Famine Early Warning Systems Network (FEWS NET) was created by the United States Agency for International Development (USAID) to provide advance warning of potential famine events and to collect data to support humanitarian response programs.

In 2003, in close collaboration with the US Geological Survey Earth Resources Observation and Science Center, the CHG was founded to support FEWS NET. The CHG's mission is to improve the early detection and forecasting of hydroclimatic hazards related to food security, droughts and floods while empowering local decision makers with improved climate analysis tools and datasets, with the overarching goal of strengthening international disaster risk reduction efforts by advancing drought early warning science.



The CHG team develops datasets and novel climate analyses, and combines them with geographic and humanitarian data to predict which areas will be most likely to endure drought or other food-limiting climatic events. This information is passed on to governments and aid organisations, allowing them to prepare for potentially devastating food shortages.

Since its formation, the group has published over 140 papers and reports, and provided access to in-depth climatic data sets to thousands of people each month. The CHG routinely contributes actionable information supporting the mobilisation of emergency relief that has helped tens of millions of people.

Moving Beyond Traditional Weather Tracking

Traditionally, rainfall estimates for a given area have been the product of observations made at weather stations and predictions based on an area's physical geography, such as elevation and distance from the equator. While these estimates hold up well when a region has many local weather stations, in the developing world observation networks are sparse.

As a result, the complex features of rainfall are poorly captured. This is particularly problematic in countries with limited weather stations and complex terrain, such as Ethiopia, Haiti, and Afghanistan, which are also vulnerable to climate extremes.

To solve this challenge, the CHG researchers have harnessed the power of satellite technology, which is able to provide regular, detailed observations of entire regions. Infrared satellite data can be used to identify cold clouds over wide areas. The CHG team has found that these measurements can be calibrated to accurately reflect fairly well both the location and intensity of rainfall in an area, even when weather stations are not present on the ground.

With each pass of the satellite, the researchers gain comprehensive information about how precipitation interacts with the geography of an area and combine these data with station observations to create the Climate Hazard Group InfraRed Precipitation with Station data (CHIRPS). The team uses CHIRPS to illuminate historical trends and rapidly identify extreme droughts. CHIRPS provides a basis for tracking hydrologic extremes anywhere in the world, even where it is not practical or possible to have people on the ground taking measurements.

Working with International Partners to Build Climate Services

A unique component of the CHG team is its international composition. Almost half of the members of the CHG team live in Africa or Latin America. These scientists work closely with local stakeholders, decision-makers and science institutions to increase disaster preparedness and guide long term 'climate-smart' development. Building on the CHG's commitment to developing datasets and tools, and harnessing the tremendous potential of satellite-based earth observations, these capacity building efforts are strengthening defences along the front-lines of climate change.

In partnership with the USGS, NASA and USAID's SERVIR, CHG works hard to put effective decision support tools in the hands of Africa and Latin America's rapidly expanding group of climate experts.

Saving Lives in Africa and Beyond

The combination of multidisciplinary scientists and humanitarian experts in the CHG and FEWS NET teams has resulted in skilful predictions of droughts.

For example, in June of 2015, the team predicted that southern Africa would experience a drier than usual rainy season that would impact both crops and livestock in the area. Monitoring of the early season rainfall performance indicated that rainfall was late in arriving and insufficient when it did arrive. Compounding this, limited governmental support and poor seed distribution in countries such as Zimbabwe reduced the opportunity to make the most of limited rainfall. As predicted, by January 2016, the region was experiencing the driest rainy season in 35 years. However, several regions were better prepared as a result of successful forecasts, preventing a far worse crisis.

Again, in the fall of 2016, CHG researchers predicted another potentially devastating drought in the eastern Horn of Africa that would continue into 2017. Indeed, this past season was one of the worst droughts in recorded history across eastern Ethiopia and Southern Somalia, with a severe lack of rainfall spreading across a much larger region than that in 2011. Thanks to the team's early warning and the effective contributions of many FEWS NET partners, an extensive multi-agency response was deployed, resulting in improved humanitarian assistance. Amazingly, despite its severity, relatively few deaths have been attributed to the 2017 drought.

This stands in stark contrast with a similar series of droughts in 2010–2011, when conflict in Somalia prevented humanitarian assistance from reaching much of the nation, and over 250,000 lives were lost to hunger.

FEWS NET's early warning system demonstrates the immense potential of bringing researchers from disparate fields together to solve a common problem. Close international partnership between multidisciplinary scientists, food security analysts and decision makers has enabled the group to develop skillful predictive models with the power to save lives. The CHG will continue to develop the drought early science supporting this process, and continue to disseminate these data sets, tools and techniques with experts in the developing world.

Meet the researchers

Chris Funk

Chris Funk is one of the founding members of the USGS FEWS NET climate science team, and Research Director of CHG. He specialises in developing dynamical and statistical models that anticipate droughts.
E: chris@geog.ucsb.edu

Gregory Husak

Gregory Husak is the Climate Hazards Group's main Principal Investigator, directing research activities at UCSB. He was instrumental in the development of the satellite-based rainfall monitoring techniques that are a critical component of the CHG's monitoring activities.
E: husak@geog.ucsb.edu

Shraddhanand Shukla

Shraddhanand Shukla also works as a CHG Principal Investigator, and leads a NASA SERVIR project focused on Eastern and Southern Africa. He is a hydrologist specialising in large-scale drought forecasting and monitoring, with regional expertise in Eastern and Southern Africa, as well as California and Nevada.
E: shrad@geog.ucsb.edu

Gideon Galu

Gideon Galu is a FEWS NET Regional Scientist in the Greater Horn of Africa and an expert in using remote satellite imagery and climate to predict seasonal food security outcomes.
E: ggalu@fews.net

Diriba Korecha

Diriba Korecha is the National Climate Scientist for Ethiopia, working with in country partner institutions to provide guidance on climate prediction and change.
E: dkorecha@fews.net

Tamuka Magadzire

Tamuka Magadzire is the FEWS NET Regional Scientist for Southern Africa. He has played a major role in developing crop water balance and climate analysis software for the CHG.
E: tmagadzire@fews.net

Alkhalil Addoum

Alkhalil Adoum is a FEWS NET Regional Scientist who specialises in monitoring growing seasons in the Sahel and West Africa.
E: aadoum@fews.net

Mario Rodriguez

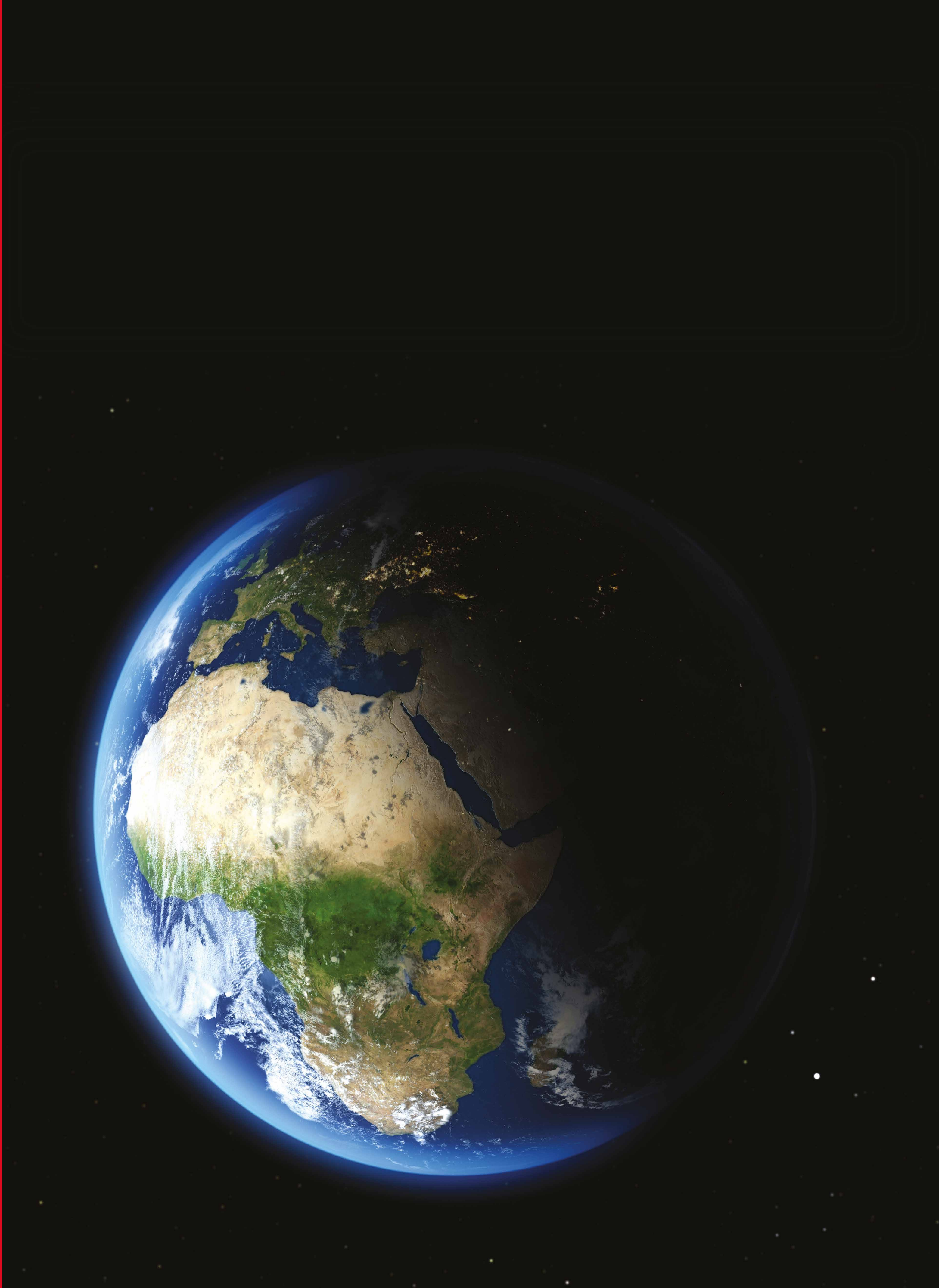
Mario Rodrigiez is a FEWS NET Regional Scientist who specialises in monitoring growing seasons in Central America.
E: mrodriguez@fews.net

Frank Davenport

Frank is a CHG research scientist whose research focuses on analysing food production and market systems and how those systems influence food security and are affected by climate change.

Website: http://chg.geog.ucsb.edu/index.html

CHG
Climate Hazards Group



LAND MANAGEMENT

PROTECTING OUR GLOBAL LANDSCAPE: FROM THE GRASS ROOTS UP

Land management involves the proactive care of our land to ensure that it meets the needs of communities, both current and future. With a distinct focus on sustainability, land management seeks to address a range of global challenges, including poverty, food security, loss of biodiversity, and climate change, at the local level.

We use up a huge chunk of the Earth's land for producing food; of the 104 million square kilometres of habitable land, half is used for agriculture alone. In fact, there is scarcely any true wilderness left on Earth, so the ways in which agricultural land is managed significantly influences the health of the natural environment and global biodiversity. Given the diversity of our planet, its inhabitants, and the complex challenges faced by specific areas and regions, bespoke approaches are inevitably required. Nonetheless, the work of researchers can inform critical developments in practice and policy worldwide. In this exciting section of Scientia, we meet the researchers conducting progressive and innovative work seeking to protect the world's landscapes for our future generations. We begin by reading about the pioneering work of Dr KC Olson and his team at Kansas State University. These researchers are seeking ways to control invasive species of weed that are destroying the native plants and wildlife of the Great Plains in America. It becomes apparent from their far-reaching work that not just one, but a range of different land management strategies, are required to successfully overcome the significant threats to the tallgrass prairie.

With our feet remaining on America's Great Plains, we then read of the work by Dr Qi Hu at the University of Nebraska-Lincoln. Professor Hu uses climate models to investigate the interactions between land use and climate change, taking a different tack toward understanding the complexities of the Great Plains and their ecosystems. We read how effective policies to manage the human impacts on our planet need to be firmly based on the rigorous scientific principles of observation, prediction, and testing, if they are to be of long-term benefit to the natural environment.

Next, we read of the work by Dr Lan Xu at South Dakota State University and collaborators seeking to protect the Northern Great Plains. The prairie ecosystems are under dire threat by dramatic agricultural expansion and invasive grass species. The challenge here is that of ensuring sufficient agricultural output while at the same time conserving the natural prairie habitats and species. The work by Dr Xu and colleagues highlights the importance of obtaining in-depth knowledge of specific habitats and inhabitants to inform the development of appropriate and effective long-term land management strategies for their protection.

We complete our exploration into land management by reading about the importance of sustainable, profitable and environmentally responsible agriculture. At Auburn University, Drs Russ Muntifering, Leanne Dillard, Kim Mullenix, and PhD student Courteney Holland, research the forage-based beef production systems of the invaluable cattle ranching economy in the State of Alabama. We read how their work directly informs management and best-practice recommendations for local farmers and as well those further afield, demonstrating the power of dissemination as a core facet of research practice.

PROTECTING THE PLAINS: A COMPREHENSIVE APPROACH TO INVASIVE PLANT CONTROL

Around the world, invasive species provide a major threat to global biodiversity. The Great Plains of the United States are among the most threatened ecosystems, where a noxious invasive weed is overpowering the native tallgrass prairies. **Professor KC Olson** and his team at Kansas State University are working to identify eco-friendly ways to naturalise the weed and preserve native prairie.

Invasive species – plants and animals that have been brought outside their native environments by human activity – are a major problem worldwide. Often invasive species have no natural predators or are unappealing to local herbivores, and thus are able to out-compete native species for resources.

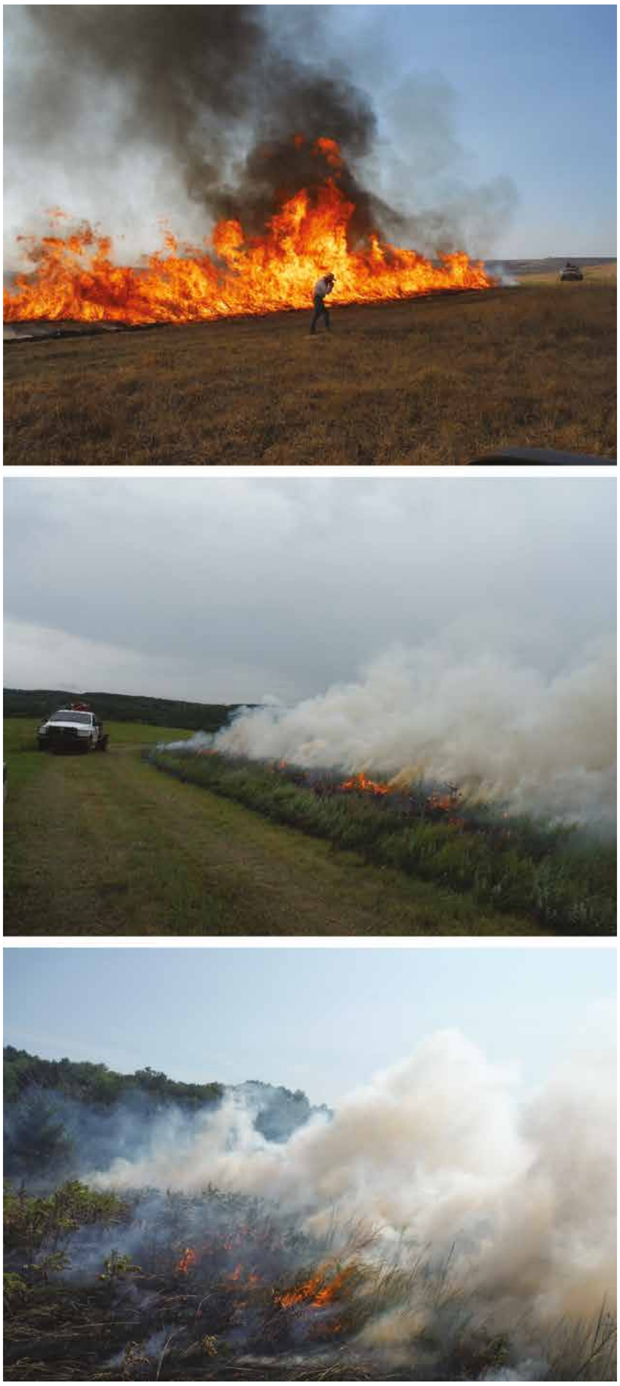
In the Great Plains of the United States, the invasive plant *Sericea lespedeza (Lespedeza cuneata;* sericea) is growing out of control, choking native plants in the region's characteristic tallgrass prairie, which is among the most endangered ecosystems on earth. Native to Asia, sericea is a perennial plant with aggressive growth and reproductive characteristics. It was originally introduced to Kansas in the 1930s for erosion control. Unfortunately, sericea is highly invasive in the central plains of the USA and it is resistant to many forms of weed control, such as common herbicide treatments and spring season prescribed fires.

Professor KC Olson of Kansas State University and his colleagues and graduate students have spent the past decade seeking to understand ways to eradicate the weed from Kansas's grasslands, using novel grazing and burn strategies.

Tempting the Bovine Palate

One of the key reasons that sericea is so hard to tame in the Kansas prairie is that the cattle that roam the grasslands simply don't want to eat it. The plant contains high levels of tannins – strong-tasting chemicals that most cattle find unpalatable. When given the option to graze pastures where the plant is growing alongside grasses, cattle opt to eat the grasses, furthering the imbalance between sericea and other species. The high level of tannins also means that the plant is harder to digest than most standard forage, so cattle also receive less nutritional benefits from grazing on sericea. When herbivores are your main line of defence against an invading weed, it is critical that they be willing and able to eat it.

After demonstrating that cattle do, in fact, show a strong aversion to hay contaminated with sericea, Professor Olson's team set out to find ways to make the plant more palatable. They discovered that a completely natural by-product of the corn milling industry called corn steep liquor (CSL) had potent tannin-binding properties. Subsequently, the group demonstrated that cows given CSL as a nutritional supplement showed an increased



Note the flame height differences and fuel condition differences between prescribed fires applied in April (top), August (middle), and September (bottom)

willingness to eat hay containing sericea and had an easier time digesting it.

In a follow-up study, Professor Olson's team noted that cattle also avoid sericea when grazing the live plant in pastures and that the live plant has even greater tannin content than it has when dried. Again, they found that supplementation with CSL made sericea more appetising to grazing cattle, and greatly improved their ability to digest it. Interestingly, their results indicate that CSL supplementation did not increase foraging rates on any other species of plants, suggesting that it is an effective and targeted strategy for controlling sericea expression in pastures, while still promoting cattle health. This presents a major win for ranchers, who can worry less about having to control the weed using herbicides.

Bringing in Backup

Another potential strategy for controlling sericea in native pastures is using additional species of herbivore to graze alongside cattle. The increase in grazing pressure caused by the addition of a second species of herbivore, effectively an increase in stocking rate, requires careful consideration. It could be detrimental to the pasture if over-grazing results, leading to soil erosion during the winter and poor forage quality the following year.

In a 2012 study, Professor Olson's team evaluated the effectiveness of grazing cattle and goats together for controlling sericea infestation in native tallgrass pastures. In their experiments, the researchers compared fields grazed by cattle alone to fields grazed by both cattle and goats simultaneously. By the end of the grazing season, they found that in fields containing both species, the percentage of sericea plants that had been grazed was significantly higher than in pastures stocked with cows alone. In addition, this co-grazing approach did not negatively affect the growth of the beef cattle, or the amount of residual forage left to protect the soil and provide food for the following year.

In another study, the team tested a rotating livestock strategy over a period of four years by comparing pastures only grazed by cattle to pastures grazed by cattle in early summer and sheep in late summer. While the weed continued to spread in the cattle only pastures, in the pastures that had hosted both types of livestock, sericea was less abundant at the end of the grazing season. Simultaneously, Professor Olson and his students studied the droppings of free-grazing cattle and sheep to determine their foraging preferences. They found that while the cattle strongly avoided sericea, sheep did not avoid eating the plant. Overall, Professor Olson's team found that the pastures grazed by sheep had significantly less sericea present over the long term, while still maintaining enough plant mass to prevent erosion over winter and provide lush pastures for the cattle to return to in the spring.

Burn Baby Burn

An approach to grassland management for plant species composition that is growing in popularity is prescribed fire. These controlled burns are often used to help prevent the accidental fires that can turn into wildfires, by clearing out the dormant and highly combustible plant materials that are most likely to burn out of control. Prescribed burns can benefit native species by creating opportunities for dormant seeds to germinate and new growth to occur.

Seeds harvested from 100 sericea lespedeza plants after the team's April, August, and September prescribed burning regimes in 2015. Clearly, seed-based reproduction is strongly suppressed when fire is applied near the end of the growing season.

The Great Plains prairies are fire-adapted, meaning that many of the native plant species respond positively to frequent fire, and may even reproduce more readily following a fire. Unfortunately, the early springtime prescribed fires that are common in Kansas appear to benefit sericea as well. Early burns are usually performed with the idea that late season burns may not leave enough vegetation to prevent soil erosion over the winter, but sericea is a late-blooming weed and is less active in the spring.

Professor Olson and his team wanted to determine if alternative burn schedules would help with the pesky plant without damaging the long-term health of the grasslands. Over a four-year period, they tracked the growth of sericea in plots that received springtime, early summer, and late summer prescribed burns.

They found that the later the burn was applied, the better the reduction in sericea, with positive impacts on many native species, including legumes and wildflowers. Later prescribed fires were also slower-moving, and thus, easier to control than traditional spring-season fires. Further, late season burns left enough ground cover so that soil was protected during the winter. The team's results demonstrate how late season prescribed burns can offer an inexpensive and effective means of controlling sericea populations, while preserving and promoting native plant species in the Great Plains.

Spray the Weeds Away

Another tactic for removing undesired plant species is applying targeted herbicides to pastures. Spraying herbicide for sericea is commonly done late in the fall, to reduce the risk of killing native species while hitting the weed when it is still active. Professor Olson's team sought to determine if using herbicides was as effective as late season prescribed burns or enhanced the results of a burn, and if either impacted native plant species.

They found that while herbicides, burns, and the two together significantly reduced sericea populations, there was little difference between the three treatments in overall effectiveness. However, native plants that had growth cycles similar to sericea were also negatively impacted by treatments leveraging herbicides. Given that prescribed burns alone provided similar sericea reduction without damaging native plant populations, the team's work reveals that applying simple late season burns is the most eco-friendly option for attacking the weed.

Boosting Bird and Butterfly Populations

A critical component of the team's work is to ensure that sericea is reduced while native plants and animals are either unaffected or stimulated. Grassland songbirds avoid nesting in areas where sericea grows heavily because the aggressive plant chokes out many of the native flowers that grassland butterflies, a food source for songbirds, rely on for nectar. This demonstrates that the invasive weed has broad-reaching impacts on grassland ecosystems. However, sericea treatments also have the potential to impact native plants and wildlife negatively, and both the risks and benefits must be considered.

Professor Olson's team performed a study in which the abundances of grassland songbirds and butterflies were measured at sites where both burn timing and multi-species grazing were compared. Neither treatment negatively affected the biodiversity of these groups. In fact, late summer prescribed burns appear to actually benefit certain grassland birds.

These results indicate that both correctly-timed prescribed burns and targeted grazing can be effectively utilised to reduce sericea invasion, while still maintaining the health of native wildlife populations.

A Better Future for the Great Plains

Controlling invasive species and protecting native plants and wildlife is critical for preserving the world's biodiversity. In the Great Plains, tallgrass prairie is threatened by rapidly spreading sericea, which has not responded to treatment with traditional methods.

Professor Olson, his colleagues, and his team of students have identified a comprehensive suite of approaches to manage sericea that can be implemented to naturalise the weed while promoting native species. By using nutritional supplements that encourage cattle to eat sericea, adding less tannin-sensitive herbivores to infested fields, and applying late summer burns to harm the weed at its peak, ranchers and land managers can control sericea while promoting the health of their herds and the native prairie grasslands.

Meet the researcher

Professor KC Olson
Department of Animal Science and Industry
Kansas State University
Manhattan, KS
USA

Professor Olson obtained his PhD in Animal Sciences and Industry at Kansas State University in 1998. Since then, he has swiftly ascended to acclaimed academic positions, including an Associate Professorship at the University of Missouri, and his current Professorship at Kansas State University. Here, Professor Olson also holds the title of W.M. and F.A. Lewis Distinguished Chair. To date, Professor Olson has been presented with ten academic and professional development awards, and has been an editor as well as a reviewer for a number of respected journals. Professor Olson has also presented at a broad range of local and international conferences as an invited speaker. With an outstanding list of successful grant funding awards and several papers already published this year, Professor Olson has contributed significantly to his field in providing expert knowledge in range beef cattle nutrition and management.

CONTACT

E: kcolson@ksu.edu

KEY COLLABORATORS

Dr Walter H. Fick
Dr David A. Haukos
Dr Gregory J. Eckerle
Dr L. Arturo Pacheco
Mr Jack E. W. Lemmon
Ms Consuelo A. Sowers
Mr Jonathan A. Alexander
Mr Garth A. Gatson
Ms Sarah B. Ogden
Mr Garrett W. Preedy

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INVESTIGATING THE ROLE OF LAND USE IN CLIMATE CHANGE

Land-use changes can have a significant effect on regional climates. **Professor Qi Hu** from the University of Nebraska-Lincoln uses climate models to study the interactions between land-use change, regional climate and large-scale atmospheric circulation. As our understanding improves, so too does our ability to create effective policies that better manage human impacts on the climate and our living environment.

Earth's Complex Climate

The complexity of the Earth's climate is difficult to fully appreciate. Developing computer models that describe the past, current and future climate takes teams of experts specialising in a multitude of different facets. It also requires experts in how these climate facets interact, since no component works in isolation.

Modern climate models include many different descriptions – from condensation in cloud formation to the chemical effects of volcanic ash, and from plant leaf morphology to ocean tides. Such models are based on forcings (any change that gives a push to the Earth's climate, such as greenhouse gases), and feedbacks (where one process influences another to change its direct effect or outcome). Human-induced changes are significantly complicating these processes, and understanding such human effects will help us to better predict disastrous climatic events or develop adaptive measures to cope.

Climate scientist Professor Qi Hu and his team at the University of Nebraska-Lincoln focus on the land and atmospheric elements of the Earth's climate system and how they interact. In some of his earliest work, Professor Hu studied the processes that produce fluctuations (or 'oscillations') in natural climate heating systems. In these systems, heat given to the Earth's climate by the Sun's incoming energy is utilised over a period of time through surface evaporation, vertical mixing (convection), and relaxation. One example is the Madden-Julian oscillation, a 30–60-day fluctuation in the atmosphere over the tropical Indian and Pacific Oceans. The influence of this oscillation is most clearly seen as fluctuations between active and absent massive convection, along with associated high rainfall followed by low or no rainfall.

There are competing theories to explain such oscillations, most invoking global-scale atmospheric dynamics to create a travelling wave around the Earth. A chance meeting in the hallways of Colorado State University led to a collaboration between Professor Hu and Professor David Randall, who had unexpectedly seen similar oscillations in his modelling results. In two papers published in 1994 and 1995, the pair showed how such oscillations could

occur spontaneously in climate heating systems where active surface evaporation occurs.

The Great Plains

The Great Plains of the US stretch over a vast swathe of the central US. In the 1930s, this region also became known as the 'Dust Bowl' after drought ravaged the area, resulting in huge dust storms. The Dust Bowl drought was devastating for individuals and the whole society of the region. Yet, the causes behind its longevity and severity are still much debated. Understanding the causes behind this drought can help us build a picture of an area's vulnerability to similar events. Such insight can also

‘Rigorous methods and analyses are essential in my work to guarantee that my findings will stand the test of time. I am also a believer that science is to directly benefit our society.’

reveal ways in which we can reduce this vulnerability through sustainable policies and practices, while also improving the natural environment.

Professor Hu built upon his work on regional climate mechanisms and forcings, and published two papers with his former student Michael Veres in 2015 and 2016, focusing on the Great Plains. In these papers, the researchers discuss the different response of the climate of the Great Plains region to the phase of the Atlantic Multi-decadal Oscillation (AMO) – a cycle of anonymously warm and cold sea surface temperatures in the Atlantic that has a measurable impact across the whole northern hemisphere.

They found that the climate of the Great Plains was more sensitive to the cold AMO sea surface temperatures and much less sensitive to warm anomalies, highlighting the complexity of making seasonal predictions in regions affected by such oscillations. This work also demonstrates the importance of considering the phase of the oscillation in any model simulations.

Some of Professor Hu’s most recent work has continued to focus on the Great Plains. He has been working with a group of scientists at the University of Nebraska-Lincoln since 2013, including his former student Jose Abraham Torres-Alavez and Dr Matthew Van Den Broeke, to investigate how land-use changes can have an effect on regional atmospheric circulation, weather and climate. In their 2018 article, the team made the first attempt to quantify the effect of land-use change on the atmospheric and precipitation rates during the Dust Bowl period.

Climate Models

The team employed modelling techniques to study the climate system of the region. They used the Weather Research and Forecasting Model (WRF, v. 3.6) to provide the weather information for the region, linked to the National Centre for Atmospheric Research (NCAR) Community Land Model (CLM, v. 4.0) – a very advanced and widely used Earth System Model.

The land element of an Earth System Model is often the one most tangible to us – this is, after all, where we live, and nowhere else in the Earth system is our effect more obvious. It is also one of the largest and most complex components of an Earth System Model, not least because of the vast number of interactions that occur between the land and other components of the model – particularly the atmosphere – over scales ranging from milliseconds to millennia, micrometres to global.

The land model is built around land-use patterns. The Community Land Model, for example, currently includes five different land uses – lakes, urban, glacier, crop and vegetation. Urban is then further broken down into five subcategories. Vegetation is broken down into ‘plant functional types’ from bare earth, to trees vs shrubs or grass, crops vs non-crops, irrigated vs non-irrigated. Each land-use type or plant functional type has defined properties, which include anything from the leaf structure, to the way water moves down through the plant, to the orientation of a nearby wall (shade or sun).

One of the most important properties of any surface, whether natural or human-made, is its reflectivity or ‘albedo’. This tells you how much radiation a surface reflects or absorbs. As a general rule, light surfaces (such as ice and snow) reflect and dark surfaces (such as dense woodland) absorb. Absorption

of radiation creates warming at the surface and in the air lying directly in contact with it – hence the strong link between the land and the atmosphere. This warming, in turn, causes the air to rise, reducing the local air pressure and setting up one of the most fundamental processes in atmospheric circulation – convection. Changing the albedo of a region through changes in land use is one of the simplest and most efficient ways of altering the radiation budget of an area and the atmospheric circulation pattern above it.

Role of Land-Use Changes

The Great Plains drought lasted from 1932 to 1938 – a period with very few external influences pushing on the climate, which makes its length and severity particularly interesting. The area is influenced by swings in tropical Pacific Ocean temperatures associated with the inter-annual El Niño Southern Oscillation (ENSO), as well as the decadal-scale AMO. These affect the amount of rainfall received in the Great Plains region. However, during this time, there were only two mild El Niño events in the Pacific, and only a weak sea surface temperature anomaly in the Atlantic associated with the AMO.

In the pre-settlement period up to the 1930s, Professor Hu and his team estimate that 43% of the native grassland and 75% of the savanna were lost to dryland crops and pastures, and that from the 1930s to the present day, this has continued to shift towards most of the croplands being irrigated to some degree. They set up a series of modelling experiments using three land-use patterns: those of the pre-settlement era; the 1930s; and finally, the present day, in order to establish what mechanisms and forcings were most important during the different time periods.

The team's results indicate that the external forcings from the mild ENSO events in the Pacific and the AMO sea surface temperatures anomalies were likely to have been the initial trigger for the drought, but that specific land cover conditions in the 1930s exacerbated the event. They found that external pushes from ENSO and AMO were weak, and that the pre-settlement era and present day were similar enough to highlight something special happening in the intervening years.

The dryland crops and pastures of the 1930s changed the surface albedo so much that there was a significant reduction in the amount of solar radiation absorbed at the surface, discouraging convection. At the same time, this also affected the regional circulation. Specifically, this land-use change altered the Great Plains southerly low-level jet, which is responsible for the transport of huge volumes of moisture up from the Gulf of Mexico and into the Great Plains, with the boundary of the jet often associated with intense convection and precipitation. The shift in the pressure gradient across the region weakened the Great Plains southerly low-level jet, thereby limiting the supply of moisture from the Gulf of Mexico. Professor Hu and his team conclude that the initiation and recovery of the drought were likely the result of larger-scale circulation changes, but that this was intensified and prolonged by regional circulation shifts due to land-use changes.

The team's work has highlighted how important it is for us to understand local and regional scale terrestrial processes and their interactions with the atmosphere in order to predict or prevent large scale, severe and extended periods of drought. This will allow better steps to be taken to improve the natural environment and assess its susceptibility to such events.

Meet the researcher

Professor Qi (Steve) Hu
School of Natural Resources
and Department of Earth and Atmospheric Sciences
University of Nebraska-Lincoln
Lincoln, NE
USA

Professor Qi (Steve) Hu completed his BS in meteorology in 1982 at Lanzhou University in China. He then moved to the US in 1984 to pursue an MS in Atmospheric Science at Colorado State University. He remained at Colorado State to complete his PhD in 1992 on the subject of low frequency oscillations in radiative-convective systems. He then worked as a postdoctoral and research assistant in New York and Washington before becoming the director of the Missouri Climate Centre, Missouri, from 1995 to 1999. In 1999, he moved to the University of Nebraska-Lincoln, where in 2009 he started his current position as Professor in the School of Natural Resources and the Department of Earth and Atmospheric Sciences. Since 2012, he has also been the editor of the *Journal for Applied Meteorology and Climatology*. He is an active member of both the American Meteorology Society and the American Geophysical Union and has advised more than 15 masters and PhD students.

CONTACT

E: qihu@unl.edu
W: http://snr.unl.edu/aboutus/who/people/faculty-member.asp?pid=54

KEY COLLABORATORS

Song Feng, University of Arkansas
Mike Mann, Pennsylvania State University
Steve Ghan, Pacific Northwest National Lab
Matthew Van Den Broeke, University of Nebraska-Lincoln

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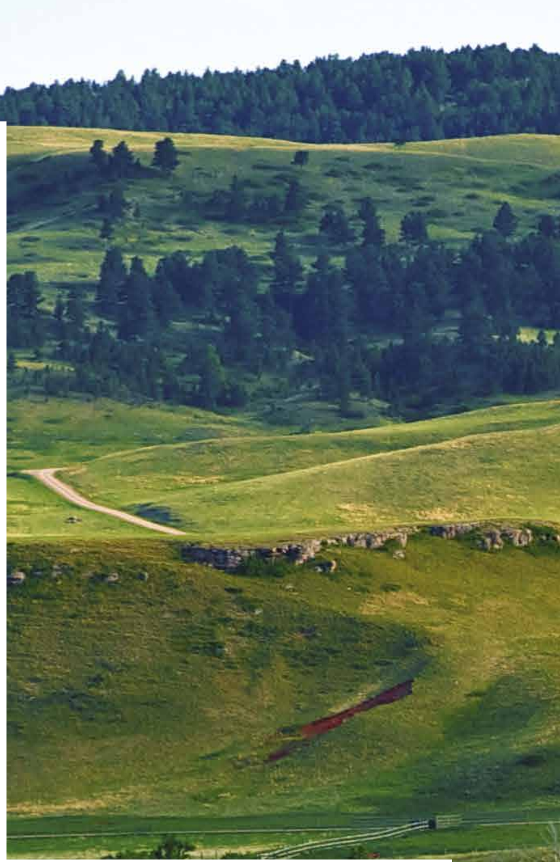
TURF WARS: THE IMPACT OF INVASIVE GRASSES ON PRAIRIE ECOLOGY



Grasslands are global biodiversity hotspots, but are severely threatened by agricultural expansion. In particular, invasive grass species can wreak havoc on wild grassland ecosystems. **Professor Lan Xu** of the Department of Natural Resource Management at South Dakota State University, along with her national and international collaborators, is investigating the ecological 'tug-of-war' between invasive and native grass species in the Northern Great Plains, and the implications for prairie land management and agriculture.

Invasive grasses in the Northern Great Plains

The Northern Great Plains (NGP) is a vast expanse of prairie grassland that spans five US states – north-central Nebraska, much of North Dakota and South Dakota, north-eastern Wyoming, eastern Montana – and two Canadian provinces. The NGP's wild prairies are an important habitat for a wide variety of wildlife. However, these have been fragmented by anthropological pressures, both historic and contemporary. Magnificent herds of bison and pronghorns were displaced by domestic cattle, and the once endless sea of wild grasses was replaced with golden wheat fields, necessary to feed the influx of settlers in the 19th century. The rapid expansion of intensive arable and livestock farming led to widespread soil erosion, resulting in poorer agricultural productivities and lower biodiversity. Native flora and fauna are necessary for maintaining healthy soils, and with their loss, soil erosion became a vicious cycle, culminating in the infamous Dust Bowl of the 1930s.

For the early settlers, the grasses native to the 'New World' were woefully inadequate for the demands of large-scale livestock grazing. Thus, they planted hardy grasses from the 'Old World', such as Kentucky bluegrass (*Poa pratensis*) and smooth brome (*Bromus inermis*). These grasses from Europe, Asia and Africa provided ideal livestock feed, being fast-growing, perennial and less susceptible to soil erosion than the native grasses. However, their introduction proved to be devastating to the prairie ecosystem. These 'alien' grasses soon became invasive by outcompeting native grasses. Prairies that once hosted diverse wild grass species were displaced by dense monocultures of smooth brome and Kentucky bluegrass. This was often accompanied with precipitous drops in the biodiversity of animals that depend on native grasses.

The decline of NPG native grasses – and the wildlife that depends on them – is as much of an issue now as it was in the 19th century. The NGP are now among North America's most threatened ecosystems – at risk of vanishing completely! It is thought that less than 1% of native tall-grass prairies remain and 70–90% of mixed-grass prairies have been lost. Previous attempts to restore the native grasslands have involved eliminating invasive grasses through control methods such as

grazing, fire and herbicides. However, these methods do not guarantee recovery by native species and very often, non-native grasses simply return with a vengeance. Such interventions have often been doomed to failure, as the mechanisms and processes underlying grass invasion and persistence in response to control methods are not fully understood.

Therefore, Professor Lan Xu and her colleagues at South Dakota State University teamed up with scientists at the US Forest Service to gain a deeper understanding of grass plant community dynamics and demographics. Such knowledge is greatly needed for developing long-term effective invasive grass management strategies.

Grassland degradation is a global issue that plays out in grassland ecosystems across the world. Therefore, its investigation, prevention and reversal often require international collaboration. Since 2012, scientists and PhD students from the China Agricultural University have joined the team. This collaborative research programme, focussing mainly on the prairies in the heart of the NGP, has been highly fruitful and synergistic.

The Bud Bank

Many plants – grasses included – reproduce sexually or asexually. Although sexual reproduction enables 'survival of the fittest' through genetic diversity, it must depend on the well-orchestrated processes of flowering, pollination and seed production. In contrast, asexual or vegetative reproduction can be quicker and produce more offspring, though these are genetically identical 'clones'. These modes of reproduction are represented by the 'seed bank' and the 'bud bank'. In fact, the bud bank is the *modus operandi* behind invasive grass species' extreme resilience and persistence, and Professor Xu and colleagues are investigating its role in their colonisation of grassland ecosystems.

Plant sexual reproduction leads to seed production, which facilitates geographic dispersal and colonisation of new habitats. However, grass seeds rarely persist for more than five years in the soil and are often disturbed by grazing. For vegetative reproduction in grasses, the units of reproduction are buds – tissues that separate from the parent plant and form new individuals. Seed and bud banks, inside the soil, allow grass populations to survive environmental disturbances, such as grazing, tilling and fire. Perennial grasses overwhelmingly favour asexual reproduction through bud banks, which can account for the formation of over 99% of grass stems in some prairie ecosystems.

In grasses, 'rhizomes' are structures within the soil that act as food stores for surviving underground and sources of new buds. These buds develop into tillers (stems) that sprout and form leaves. This 'tiller recruitment' from the underground bud bank is the means by which invasive grasses spread and penetrate adjacent prairie communities and persist. Although elimination of above-ground stems through conventional control methods may seem effective, as long as the bud bank remains intact, invasive grasses will often return.

The bud bank is instrumental to maintaining grass population dynamics and conferring resilience to harsh environmental stresses. Buds can lay dormant for long periods, and become 'activated' to enable rapid compensatory growth following disturbances such as grazing, fire and haying. Compared with native grasses, invasive grasses often have bud banks with greater reproductive capability – showing superior bud outgrowth (buds transitioning into stems) under a wider range of environmental conditions.

The competition for natural resources – space, soil nutrients, water, light and pollinators – plays out underground between the bud banks of invasive versus native grasses. This ecological tug-of-war happens unseen, beneath our feet, in grasslands across the world. Although hidden, it has very real, devastating impacts not only on grassland biodiversity, but also on agricultural productivity. Wild grasslands are important for global nutrient cycling, and are habitats for pollinating insects and pest-eating predatory birds that are also deployed in agriculture.

In South Dakota, Professor Xu and her collaborators carry out ecological field studies and controlled growth chamber experiments, to investigate bud bank dynamics, and the physiological basis of invasive species' apparent winning streak. Importantly, they discovered that damaging invasive smooth brome by mowing (simulating grazing and haying) during its vulnerable growth stage hindered bud formation and tiller recruitment. These findings are highly significant, demonstrating that repeated mowing could form the basis for a long-term management strategy, by effectively reducing brome's vegetative reproduction capability.

The impact of climate change on invasive grasses has been a lively field of research. Temperature, carbon dioxide levels, and inter-annual variability in precipitation are predicted to increase in the NGP. So, how will these environmental changes, combined with livestock grazing, affect the ecological tug-of-war?

To answer this, Professor Xu's group carried out controlled growth chamber experiments. They exposed native western wheatgrass (*Pascopyrum smithii*) and invasive smooth brome to clipping effects (to simulate grazing), and different temperatures and watering frequencies, to simulate various climate change scenarios. The team found that smooth brome had greater tiller reproduction than wheatgrass at all temperatures, precipitation frequencies and simulated grazing. They also discovered that tiller reproduction was largely independent of moisture conditions for either species, though wheatgrass had greater rhizome production under moderate precipitation intervals.

Simulated grazing (clipping) was more detrimental to the native wheatgrass, which suffered from greater bud death and reduced bud development. These findings are highly insightful – suggesting that invasive brome will still have a competitive edge over native wheatgrass even under projected harsher climatic conditions, but climate change will not shift the tug-of-war! Professor Xu and her colleagues plan to further investigate the impacts of competition on bud bank dynamics under various climate scenarios.

Dropping Like Butterflies

South Dakota's Prairie Coteau plateau is the largest remaining tract of native northern tallgrass prairie in the United States and is a hotbed of biodiversity. However, it is a highly threatened ecosystem due to the expansion of arable agriculture and invasive grasses. In recent years, high grain prices have incentivised the conversion of large tracts of Coteau grassland into cropland.

Professor Xu's group has worked closely with the South Dakota Wildlife Action Plan (SDWAP) – a conservation initiative that aims to preserve the state's remaining habitats and curb loss of species – especially those of 'greatest conservation need'. These threatened and endangered species include some wetland fishes and several butterflies – including the Dakota skipper (*Hesperia dacotae*), a species that Professor Xu's group is investigating as an indicator of a prairie habitat's ecological health.

The Coteau's decline in native butterfly populations is a high-priority conservation concern for the SDWAP. In the last decade, the population of the Poweshiek skipperling (*Oarisma poweshiek*) – a once common butterfly – has experienced population collapse. The threatened Dakota skipper has also experienced a precipitous decline, but is faring slightly better. It is hoped that the Poweshiek skipperling's sad demise is a fate that does not befall the Dakota skipper or other SDWAP-prioritised butterfly species. As well as habitat fragmentation, it is thought that suboptimal prairie management schemes may contribute to the decline in insect biodiversity. Controlled fires are often used for prairie management and recovery, but in the wrong season, fire can kill butterfly larvae.

Identifying high quality prairie habitats is instrumental to implementing appropriate prairie management schemes and incentivising conservation on public, tribal and private lands. Professor Xu's team have deployed NASA-acquired Landsat satellite aerial imagery to map and delineate 225 square miles of South Dakota's Coteau prairie habitats. They then assessed the ecological condition of the mapped land and quantitatively characterised native vegetation, and compared this to sites inhabited by Dakota skipper butterflies. This enabled them to identify sites within the study area where Dakota skippers are likely to thrive – using space age technology as a 'down-to-earth' approach to prairie conservation!

Summary

The NGP's prairie ecosystems are under threat from invasive grasses and agricultural expansion. There are no easy fixes – after all, we need crops to eat, but we also have a duty to help conserve this important ecosystem. Unfortunately, interventions for native grass recovery or prairie management often fail or cause further damage. Therefore, in-depth knowledge of the ecology of grasses and the organisms that inhabit these habitats is needed.

To plug this knowledge gap, Professor Xu and her colleagues are investigating the 'bud bank' – the secret weapon of invasive grasses that gives them an edge over native grasses. The research group hopes to use their findings to develop effective grass management strategies that will result in successful native grass recolonization across the globe.

Meet the researcher

Professor Lan Xu
Department of Natural Resource Management
South Dakota State University
Brookings, SD
USA

Professor Lan Xu is a professor at the Department of Natural Resource Management at South Dakota State University (SDSU). Her research interests include spatial distribution of vegetation in relation to environmental gradient factors, vegetation succession in semi-arid and arid regions, plant-animal interactions, and especially the ecology of the 'bud bank'. Professor Xu has long had a fascination with plant ecology. After achieving her BS degree in Botany at Shanxi University, China and a MS in Plant Ecology at the Institute of Applied Ecology, Chinese Academy of Sciences, China, she gained a PhD in Plant and Rangeland Ecology at North Dakota State University, USA, in 1998. After graduate school, she was hired as a Research Associate at South Dakota State University, and rose to the ranks of Assistant Professor, Associate Professor, and then Professor, in 2017. As well as undertaking research, she advises a number of graduate students and undergraduate researchers, and teaches several courses, including Plant Ecology, Advanced Plant Ecology, Field Ecology, and Principles of Ecology.

CONTACT

E: lan.xu@sdstate.edu
W: https://www.sdstate.edu/directory/lan-xu

KEY COLLABORATORS

Dr Jacqueline P. Ott, US Forest Service, Rocky Mountain Research Station
Dr Arvid Boe, South Dakota State University
Dr Yuping Rong, China Agricultural University
Dr Jack L. Butler, US Forest Service, Rocky Mountain Research Station
Dr John Hendrickson, Northern Great Plains Research Laboratory, USDA-ARS
Dr Patricia S. Johnson, South Dakota State University
Dr Yingyun Zhang, China Agricultural University

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South Dakota State University

GREENER PASTURES: TRANSFORMING LAND MANAGEMENT PRACTICES IN THE CATTLE INDUSTRY

In the face of global climate change and challenges to sustainable use of renewable resources, farmers and ranchers are continually seeking best management practices that are economically viable and environmentally friendly. To meet this need, researchers at Auburn University are conducting innovative agricultural research directed at shaping sustainable cattle ranching practices and pasture management techniques.

In the Southeast United States, the State of Alabama runs on agriculture. With over four million acres of pasture-land, the state is poised for a booming cattle ranching economy. Faculty members Russ Muntifering, Leanne Dillard, Kim Mullenix and Courteney Holland in the Department of Animal Sciences at Auburn University are studying how the composition, biology, and management of forages in cattle pastures affect the nutrition and health of beef cattle and impact the local ecosystem. The research team's work is shaping pasture management practices in Alabama, with implications for how grasslands for raising cattle can be sustainably managed worldwide.

Healthy Pastures in the Face of Climate Change

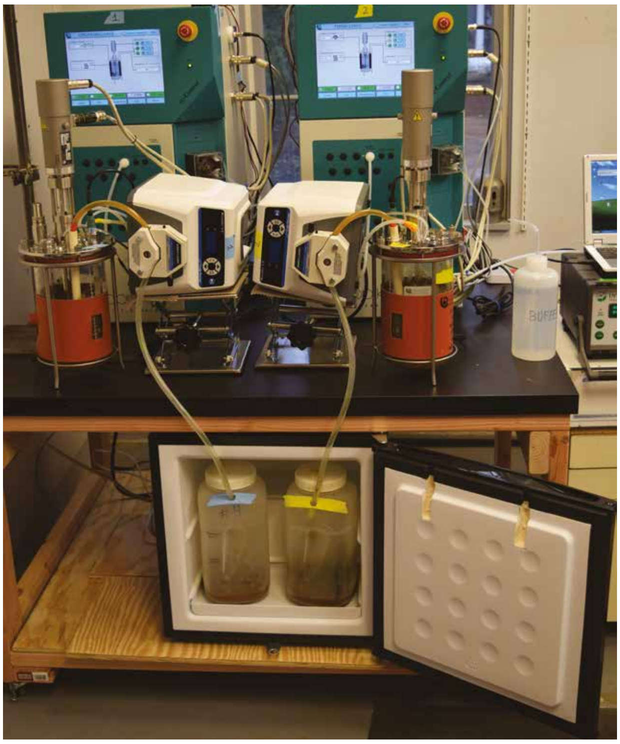
Understanding how climate change and pollution impact agricultural practices, particularly as they relate to forage for cattle and other livestock, is a key component of the research carried out by Dr Muntifering and his colleagues. Many estimates of plant growth under future climate scenarios focus on elevated carbon dioxide, which is typically reported to have a neutral or even positive impact. It is commonly held that elevated carbon dioxide increases plant yield and is protective against other environmental stressors.

However, the increasing greenhouse gasses associated with global climate change also include ground-level ozone, a major component of urban smog that is extremely toxic to plants. 'Once thought to be confined to large metropolitan locales, ground-level ozone is now known to be transported long distances to rural areas such that many of the world's most productive agricultural and forested regions are currently exposed to harmful levels,' Dr Muntifering explains.

The team has spent years analysing the chemical composition and nutritive value of common forage plants under different carbon dioxide and ozone exposure conditions in controlled experiments as well as natural settings. They have found that grasses and legumes such as clovers exposed to injurious levels of elevated ozone have less biomass yield and digestible content than non-exposed plants, meaning that a cow would have access to less forage that is also of lesser quality in an ozone-polluted pasture than one with clean air. Furthermore, contrary to popular belief, the team discovered that heightened carbon dioxide levels do not protect these plants from ozone damage, nor do they offer any effects that compensate for the loss of nutritive value.

These findings have critical implications for the agriculture community worldwide, and have garnered international attention for the potential impacts they suggest. While many studies have focused on the overall yield of forage plants when assessing potential climate change related losses, the team has demonstrated that nutritional quality can be impacted independent of a plant's overall yield. In the United States alone, these effects could cost billions in lost production and necessitate the development of more robust pasture management and grazing strategies.

'These findings represent a significant departure from the conventional wisdom on elevated carbon dioxide effects on plants, and further illustrate the need for manipulative "real world" experiments in climate-change research that utilise environmentally relevant exposures of mixtures of common air pollutants, not simply individual pollutants as have been utilised traditionally in controlled-environment experiments,' Dr Muntifering notes.



Reducing Greenhouse Gases

Like carbon dioxide and ozone, methane is a greenhouse gas that is tightly tied to both climate change and the cattle ranching industry, as cattle produce high levels of methane when digesting common pasture grasses. A major goal of sustainable beef livestock nutrition is identifying mixtures of feed that reduce methane emissions while still producing cattle with high body weights.

Dr Dillard has found that incorporating annual Brassica species, such as turnips, and summer crops, such as sorghum, into grazing crops provides beef cattle with higher nutritive value, while also reducing their methane emissions up to 30% by stimulating the efficiency of the cattle's gut bacteria. Another benefit is that incorporating these plants is often less expensive than nutritional supplementation and provides a much greater biomass of forage for the herds. This work demonstrates that pasture management practices can reduce methane production while maintaining high quality grazing for a herd at a lower cost, allowing ranchers to decrease the impact of beef production on the environment while maintaining a profitable business.

Maintaining Grassland Ecosystem Health

Another aspect of the team's work is understanding how fertilisation efforts impact nutrient cycling in cattle fields. Animal wastes are high in phosphorus – a mineral that is often beneficial to plants and is a primary component of manure-based fertilisers. Often these fertilisers are applied at higher rates than growing plants will use, thus extra phosphorus is left in the soil. This problem is magnified in fields designated for cattle grazing, where urine and manure contribute phosphorus at a much higher rate than the typical grasses grown in the field will ever use. Dr Dillard and her colleagues wanted to understand how different land management practices could help prevent such high levels of the mineral from accumulating in soil in the first place, particularly by understanding how fertilisation with other nutrients impacts phosphorus levels in cattle fields.

Over three years, the group monitored phosphorus activity in cattle fields that were seeded with grasses and clover in spring, and cowpea in summer. Different fields were treated with nitrogen fertiliser at the recommended dose, half the recommended dose, and no nitrogen. The team found that fields fertilised with nitrogen at half the recommended treatment levels had the highest forage mass for cattle while also decreasing levels of phosphorus in the soil. Notably, increasing nitrogen to the full dose did not improve these results, suggesting that cattle farmers can use less fertiliser to provide their animals with lush forage, while also helping prevent excessive phosphorus levels that could end up in waterways later.

Nitrogen fertiliser represents the single greatest input cost of improved-pasture production for grazing by stocker cattle. There is an increasing need to boost forage supplies while simultaneously reducing inputs of nitrogen fertiliser. This is due to the finite supply of fossil fuel needed to manufacture fertiliser, the potential for an unstable supply chain, and our increasing global population.

The team is currently investigating biofertilisation with plant-growth-promoting rhizobacteria (PGPR) as an alternative to manufactured nitrogen fertiliser. In addition to enhancing pest resistance and drought tolerance, PGPR promote plant growth as a result of increased nutrient uptake from soil. Small-plot studies with select strains of rhizobacteria have revealed positive effects on forage nutritive quality and nitrogen-use efficiency, and the team plans to evaluate this on a larger scale to include hayed and grazed pasture.

Alternative Winter Systems for Cows and Calves

An important component of keeping cattle in seasonal climates is stockpiling forage for them to consume during the winter months when pastures are dormant, or grazing cool-season forages. Without a high-quality supply of grazeable forage,

farmers must turn to expensive feed supplements to maintain the body condition of beef cattle through the winter.

Stockpiled forage serves as a sufficient replacement for hay if managed properly. Grazing stockpiled forage is an economical alternative to cutting and baling hay. Feeding lactating cows through the winter poses a major challenge, as their body condition must be maintained at low cost to ensure profits. To reduce overwintering costs while maintaining a productive and healthy herd, farmers need to be aware of which forage varieties and management practices will provide high yield, high nutrition forage for their cattle.

In the Southeast US, bermudagrass is a popular perennial grass for pastures. Hybrid varieties, bred with yield, nutritive value, and digestibility in mind, provide high quality forage for cattle during the warmer months, and are highly suitable to stockpiling for winter feeding. It is common practice for pregnant or lactating cows to be supplemented with hay or other feeds during the colder months. However, the amount of supplementation can be decreased by adding stockpiled forages.

Courteney Holland recently evaluated whether pasture management practices could help keep the quality of stockpiled bermudagrass high enough to support the nutritive needs of lactating cows without expensive supplementation. She found that cows fed stockpiled bermudagrass grown in fertilised fields maintained body weight better and had pregnancies and calves that were just as healthy as those fed nutritional supplements with standard hay. This also came at a lower cost compared to using supplements.

A similar study conducted by Dr Kim Mullenix with stockpiled bermudagrass supplemented with locally available by-product feeds for stocker calves suggested that this system may serve as a viable alternative to traditional conserved forage approaches for managing weaned calves during the fall forage production gap.

'Using cool-season forages is an economically feasible practice that can be used by cow-calf producers to extend the grazing season in the winter months, and research efforts among our group have focused on optimum combinations of species for use in our climate,' says Dr Mullenix. The team showed that cool-season annual grasses such as oats, rye, triticale, and ryegrass could successfully support high levels of gain and more than 100 grazing days per year for stocker cattle and cow-calf systems.

These results support the idea that targeted field management practices can help reduce farm costs while still maintaining a healthy herd. 'Research in this area could have measurable impact on rebuilding cow herd numbers in the State of Alabama from its current historically low inventory,' notes Holland and Dr Mullenix.

A Greener Future for Alabama Cattle

The team's research is identifying practices that can make cattle farming in Alabama and the Southeast US more economical and sustainable, protecting land, animals and the economic interests of farmers.

Through their Extension programs, the group works directly with farmers to provide up-to-date beef cattle and forage management recommendations based on their research findings. A key component of their efforts is disseminating best practices to ranchers both locally and worldwide through novel delivery methods. The team is working to make this information actionable and accessible to farmers through the development of online decision tools related to land and nutritional management, hands-on educational programming for farmers, and interaction with state, federal, and local industry to disseminate information to the public. Providing outreach to farmers helps bring adoption to practical sustainable land and animal management practices, which is a key focus of the research team.

When describing the efforts of the team, Dr Muntifering states: 'We stand shoulder-to shoulder as a genuinely integrated team of teaching, research and extension professional peers engaged in forage-based beef production systems… our achievements are a collective result of collaboration among our team.'

Meet the researchers

Dr Russell Muntifering

Dr Russell Muntifering was awarded his PhD in Agricultural Biochemistry & Nutrition from the University of Arizona in 1980. He worked as an Associate Professor at the University of Kentucky and Associate Director of the Montana Agricultural Experiment Station at Montana State University, prior to joining Auburn University as Associate Director of the Alabama Agricultural Experiment Station. Here, Dr Muntifering currently serves as a Full Professor in the Department of Animal Sciences. His research focuses on the productivity and nutritive quality of forages for agricultural livestock.

E: muntirb@auburn.edu
W: http://ansc.auburn.edu/muntifering/

Dr Leanne Dillard

Dr Leanne Dillard was awarded her PhD in Animal Science and Ruminant Nutrition at Auburn University in 2013. After graduation, she worked as a post-doctoral fellow in the Department of Crop and Soil Sciences at the University of Georgia, and also conducted post-doctoral research with the United States Department of Agriculture-Agricultural Research Service. In 2017, Dr Dillard joined the faculty at Auburn University, where she currently holds a split appointment as an Assistant Professor between the Departments of Animal Science and Crop, Soils, and Environmental Sciences. Her research and extension programs specialise in livestock pasture-based nutrition and forage crop production.

E: dillasa@auburn.edu
W: http://ansc.auburn.edu/leanne-dillard/

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AUBURN UNIVERSITY

Dr Mary Kimberly Mullenix

Dr Kim Mullenix completed her BS and MS in Animal Science and Ruminant Nutrition at Auburn University, before earning a PhD in Agronomy from the University of Florida in 2013. In 2014, she returned to Auburn University as an Assistant Professor in Animal Sciences, where her research focuses on improving forage and nutritional management strategies among beef cattle operations, with the goals of optimising land use and improving economic returns. Through her Extension program, she develops educational programming for beef farmers on improved nutritional management concepts. Dr Mullenix is passionate about education and outreach, and has been awarded the *Auburn University College of Agriculture/AAES Excellence in Extension and Outreach Award* and the *Alabama Beef Cattle Improvement Association Outstanding Extension Educator Award.*

E: mullemk@auburn.edu
W: http://agriculture.auburn.edu/people/kim-mullenix-3/

Courteney McNamee Holland

Courteney Holland completed both her BS and MS in Animal Sciences at Auburn University, before joining the Mullenix lab as a PhD student in 2017. Her research has focused on the impacts of nitrogen fertilisation on stockpiled bermudagrass as winter forage for cattle and sustainable equine pasture systems. Through her Extension work, she develops science-based programs to address equine pasture health and equine management practices. For her research and outreach activities, Holland is a recent recipient of the *Outstanding Graduate Student Award* and the *Meriweather Leadership Award* at Auburn University.

E: CEM0022@auburn.edu

FOOD AND HUMAN BEHAVIOUR

UNDERSTANDING THE ATTITUDES AND BEHAVIOURS OF PRODUCERS AND CONSUMERS

As we've seen throughout this edition, important factors that will guarantee a sustainable food supply into the future are healthy soil, water availability, effective land management and resilience in the face of climate change. However, the amount and types of food required, along with the resulting environmental impacts, are not determined by these factors alone, but also strongly depend on human behaviour and choices.

Therefore, in order to ensure food security into the future, a thorough understanding of the behaviours and attitudes of both food producers and consumers must also be achieved. This is the focus of the final section of our special edition on sustainable agriculture. Throughout this section, we highlight the importance of collaboration between scientists, industry and consumers, drawing expertise from psychology, sociology, ecology, climate science and economics, towards ensuring sustainable and practical food production.

First in this section we meet Dr Lynda Deeks of Cranfield University, Dr Chantelle Jay of NIAB EMR, and Dr Laura Vickers of Harper Adams University. Their aim is to develop an interdisciplinary community of scientists and industry stakeholders in the edible horticulture space, to facilitate innovation and expansion of fresh fruit and vegetable production. Through their multifaceted work, the team is also identifying areas where shaping the behaviours of gardeners and horticulture supply companies can drive the most meaningful impacts for the environment.

Next, we introduce Dr Andrew Scheld and Dr William Goldsmith from the Virginia Institute of Marine Science at the College of William & Mary, who are working to understand what motivates fishermen to target Atlantic bluefin tuna. Collaborating with the fishing community, the research team investigates how sustainable management of the Atlantic bluefin tuna can be enhanced by better understanding the motivations that underly fishermen's behaviour. The team's work is critical to the conservation of this legendary species.

In our final article of this section, and indeed the edition, we showcase research investigating the economic, social, psychological and physiological factors that influence consumers' food choices. Here, we meet researchers from the Agribusiness, Food, and Consumer Economics Research Center (AFCERC) at Texas A&M University, who address practical problems affecting the agribusiness community, both domestically and globally. By providing analyses, strategic planning, business analytics, and forecasts of market conditions that impact agricultural and food industries, the team's aim is to inform agricultural and food policies that best allocate resources to ensure a safer, affordable and nutritious food supply.

WORKING TOGETHER TO ACHIEVE A BETTER FUTURE FOR THE HORTICULTURAL INDUSTRY

The production of fresh fruit and vegetables, and ornamental plants, is often taken for granted. While producing horticultural crops and plants offers many societal benefits, it can also have negative impacts on the environment and even on crop production itself. Finding solutions that promote the benefits but reduce the impact of horticulture, through collaboration with industry and research organisations, has been the focus of **Drs Lynda Deeks**, **Chantelle Jay** and **Laura Vickers**, NERC Knowledge Exchange Fellowships.

When asked to describe nature, most people will speak of remote places untouched by human hands. However, humans are part of nature, and so are the plants we think of as decorative or agricultural as we tend them in our homes and fields.

Collectively, gardens make up the majority of natural space in industrial nations' urban areas. These small green spaces have a major impact – reducing carbon dioxide and air pollution, providing shelter for pollinators and other wildlife, and providing accessible sources of fresh edible produce in urban areas. Shaping green gardening practices on a broad scale can benefit biodiversity, improve water conservation, and help protect pollinators.

Edible horticultural crops contribute to the availability of food and to a nutritious diet. However, increasing demands on production, from a growing population, risk compromising the environment that supports food production. To secure future food supplies, novel approaches to the ways that we grow, store and transport produce are needed to make food production systems more efficient and less environmentally-damaging.

In order to drive adaptation and change, closer collaboration between industry and research organisations needs to be supported. Through such collaboration, scientists can gain a clear understanding of what industry needs, while industry can provide practical support and feedback to scientists.

To bridge this gap, Dr Lynda Deeks of Cranfield University, Dr Chantelle Jay of NIAB EMR, and Dr Laura Vickers of Harper Adams University, recently received Horticultural Knowledge Exchange (KE) Fellowships. Funded collectively by the Biotechnology and Biological Sciences Research Council (BBSRC), National Environmental Research Council (NERC) and Horticulture Innovation Partnership, the KE Fellowships were awarded to the Fellows to engage in activities that accelerate the economic and social influences of collaborative research, by working with industry, NGOs and government stakeholders to maximise impacts.

Specifically, the key focuses of the Fellowships were to develop an interdisciplinary community of scientists and industry stakeholders in the edible horticulture space, to facilitate innovation and expansion of fresh produce production, and to identify areas where shaping the behaviours of gardeners and garden supply companies can drive the most meaningful impacts for the environment.

Bringing Everyone to the Table

To begin to understand the perspectives and challenges associated with the production of fresh produce, Dr Deeks and Dr Jay developed a survey that was distributed across the wider edible produce industry and the scientific community. The survey probed how industry felt science contributed to their business innovation, and explored how easy they felt it was to engage with the scientific community. Of the industry respondents, 91% felt that science had contributed to their business efforts over the past 10 years, particularly in the areas of crop yields, crop protection, better indoor growing technology, and more efficient labour and resource usages. Most were gleaning this information from industry meetings, such as the Horticulture and Potato Initiative (HAPI), the internet, and trade association communications.

Despite an overwhelming consensus that past research had benefited their efforts, an interesting trend emerged when participants were asked 'Do you feel scientific research is addressing the questions you need answers to in order to remain competitive, productive, and meet future challenges?' Only 58% responded 'yes'. The people who felt current research would benefit them in the future were the same ones who felt they had influence over what was being researched.

Findings indicate that one of the best ways to encourage industry buy in to research is to ensure that industry stakeholders feel like they have a voice in research activities. This view is further supported by the fact that the majority of respondents that indicated they had been involved in previous research initiatives also indicated that they thought current research could benefit them. The majority of participants also indicated that they would be willing to participate in future research initiatives, suggesting that increasing industry collaboration in horticulture research could lead to a greater willingness from industry stakeholders to support scientific programs related to their business.

In a complementary survey issued to the scientific community, scientists highlighted that finding industry partners was often difficult. By pinpointing the gaps preventing effective collaboration, this survey could help facilitate more of these partnerships in the future.

A focal group for workshops by the Fellows was HAPI, which consisted of fresh produce industrialists and research organisations brought together through participation in a collaborative science programme sponsored by BBSRC, NERC and the Scottish Government. This community offered the opportunity to engage with and stimulate dialog between representatives of industry and the science community. Using carefully designed workshops, it was possible to tease out key challenges and barriers that were preventing innovation, as well as strategic themes for further scientific enquiry to advance the sector.

The workshops highlighted several key challenges facing the sector, including finding ways to protect crops while using pesticides responsibly, working out supply chain issues that lead to food waste or poor produce quality, identifying horticulture practices that are more resilient to climate change and extreme weather, and recognising the need for practices that are both economical and environmentally friendly.

The participants also identified areas of research opportunity, such as increased knowledge exchange between interdisciplinary experts, using socially acceptable genetics to advance plant breeding, identifying new crop varieties, and leveraging new technologies to improve efficiency in crop management.

Guiding Practices

Complementing the work carried out by Drs Deeks and Jay, Dr Vickers focused on understanding how small-scale home garden practices can have major impact when practiced across a large enough portion of the population. When these individual practices are supported by and coupled with efforts from the ornamental industry and local planning efforts, the potential for genuine environmental benefit grows even larger.

Individual gardeners can adopt many strategies to make their gardens more sustainable. To make gardens more safe and friendly for pollinators and wildlife, gardeners can adopt a number of strategies. They can use ground cover and mulch to prevent weeds rather than herbicide, incorporate a variety of plants that attract birds and bees, use pest traps rather than pesticides, install boxes for birds and bats, and maximise green spaces by planting in non-traditional places, like the roof of a garden shed. Home gardeners can practice water and soil conservation by harvesting rainwater and reusing water, watering later in the day, minimising chemical fertiliser and peat use, and composting kitchen waste.

Dr Vickers emphasises that one of the biggest impacts that home gardeners can have on the environment is with informed selection of the plants they will use in their gardens. Consumer demand for locally sourced and native plants helps reduce the number of plants imported, subsequently reducing the risk of introducing diseases. Native plants help to support native wildlife, and often do so when planted along with a mix of non-native plants that benefit pollinators by flowering at different times throughout the season. Further, selecting plants that will thrive in the unique conditions of a given garden, be it poor soil, shade, or waterlogged, can help reduce the risk of plant loss while creating a lower maintenance landscape.

With ornamental plants, there are a number of actions that the industry can take to help support more sustainable gardening practices on a broad scale. Many are educational, such as providing clear messaging and guidance to customers about sustainability topics. This might be as simple as labelling items as pollinator friendly or locally sourced, and providing information on water saving techniques, composting food waste and other urban waste, and environmentally friendly pest management options.

In addition to educating customers, ornamental producers and retailers could make efforts to employ management practices that reduce the risk of disease that could include more locally sourced plants, follow sustainable pest management practices, offer product lines for sustainable gardening techniques, and use minimal packaging or degradable packaging when selling plants.

To ensure that these practices continue to follow the most recent research-backed recommendations, it is essential that lines of communication stay open between scientists and trade professionals. Such collaborations can be further facilitated through partnerships with organisations such as the Royal Horticultural Society.

Moving Forward

To make further impacts in sustainable horticulture, the KE Fellows have identified key areas for future research and collaboration, including crop productivity, mechanisation of operations for high quality, challenging crops and resource protection.

Dr Deeks intends to continue to support engagement between the edible produce industry and science, and to advancing our understanding of the role soil health plays in the efficiency of plant production. Dr Jay will help to disseminate outputs from the HAPI projects. Meanwhile, Dr Vickers plans to focus on quantifying the effects of different types of plants when used in various garden and ornamental landscaping structures, and bridge gardening, green spaces and edible produce through urban farming, by collaborating with businesses, municipalities, cities, commercial producers and citizens. Together, these initiatives will help grow a sustainable horticulture sector for a healthier planet and for the benefit of its citizens.

From left to right: Lynda Deeks, Chantelle Jay and Laura Vickers

Meet the researchers

Dr Lynda K Deeks
Cranfield Soil and Agrifood Institute
Cranfield University
Cranfield, UK

Dr Lynda Deeks is an experienced soil physicist/hydrologist at Cranfield University who is interested in soil structure and health. Stakeholder engagement is an important component of her role, both championing industry driven science and translating science to end users. She has used her Knowledge Exchange Fellowship to understand the innovation requirements of the horticulture and potato industry, building networks between research and industry communities, disseminating science to the horticulture and potato community, and identifying key challenges and barriers facing these industries to inform future research initiatives.

CONTACT

E: l.k.deeks@cranfield.ac.uk
W: https://www.cranfield.ac.uk/people/dr-lynda-deeks-788815

Dr Chantelle N Jay
NIAB EMR
East Malling, UK

Dr Chantelle Jay is a science communication specialist, with an MSc in Science Communication. She is also an experienced researcher specialising in integrated pest management of horticultural crops, developing low input systems for crop management. The Knowledge Exchange Fellowship has allowed Dr Jay to help to build networks amongst the horticulture community and increase knowledge exchange between partners as a potential way to stimulate innovation. Understanding the key challenges scientifically and the barriers to ensure effective uptake from knowledge exchange is key. She is currently helping to disseminate outputs from the HAPI projects.

Dr Laura H Vickers
Crop and Environment Sciences
Harper Adams University
Newport, UK

Dr Laura Vickers is a researcher and lecturer at Harper Adams University who specialises in the agronomic and biological factors that impact crop quality and productivity. Her work seeks to understand interactions between plants, insects, horticulture practices, and the climate at large. She uses this knowledge to find ways to shape horticulture practices that will be robust in the face of global challenges, such as climate change. Her research is driving conversations between horticulture industry and government stakeholders to identify areas where investment in innovation will deliver meaningful societal benefits.

CONTACT

E: lvickers@harper-adams.ac.uk
W: https://www.harper-adams.ac.uk/general/staff/profile.cfm?id=201183

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Horticulture Innovation Partnership

ANGLER ATTITUDES: UNDERSTANDING ATLANTIC BLUEFIN TUNA HARVESTS

Scientists from the Virginia Institute of Marine Science at the College of William & Mary are working to understand what motivates fishermen to target Atlantic bluefin tuna. Collaborating with the fishing community, the team surveyed over 5,000 bluefin tuna fishermen to inform sustainable management efforts and maximise fishermen welfare across the Northeast Atlantic coast of the United States. The team's work is critical to the conservation of this legendary species.

Unearthing Fishermen's Motivations

Reaching upwards of 450 kilograms in mass, the Atlantic bluefin tuna is a powerful creature, and catching one is an esteemed prize. Because of the size and speed of these apex Atlantic predators, their value is measured in more than just their taste. For fishermen, hooking and catching a giant bluefin tuna is a symbol of skill, endurance, and prestige.

Because of their global appeal for use in sushi, bluefin tuna are in high demand. Fishermen can be paid upwards of $10,000 for a large bluefin tuna, which creates big business and even bigger competition for this marine resource. As a result, the bluefin tuna is one of the most sought-after fish in the Atlantic Ocean.

The fish has a large geographic range, populating areas across the Atlantic Ocean from the equator to the Arctic and spawning primarily in the Mediterranean Sea and Gulf of Mexico. Because of their large range and highly migratory behaviour, competition among nations and fishermen for catches is fierce. Furthermore, monitoring stocks and regulating catch limits can be complicated.

Thanks to concerted rebuilding efforts that limit harvest rates on both sides of the Atlantic, there is mounting evidence that the species is recovering after decades of overfishing. However, uncertainty over population structure and dynamics, combined with the threat of illegal fishing, means that managers must remain vigilant.

Managing fisheries, such as those that target Atlantic bluefin tuna, can be challenging because each participant may be driven by a different motivation. For example, commercial fishermen may be motivated by profit, whereas understanding what recreational anglers hope to gain from their experiences on the water is less clear. Scientists and managers must work together to tease out these motivations in order to keep this fishery thriving.

'Without understanding what gets fishermen out on the water, it is challenging to predict how fishing activity and harvest patterns may

CREDIT: Captain Bobby Rice/fishreeldeal.com

‘Without understanding what gets fishermen out on the water, it is challenging to predict how fishing activity and harvest patterns may change as fishery conditions – fish availability, regulations and costs – change’

CREDIT: Captain Dom Petrarca

change as fishery conditions – fish availability, regulations and costs – change,’ expresses Dr William Goldsmith from the Virginia Institute of Marine Science at the College of William & Mary.

Dr Goldsmith and his graduate co-advisor Dr Andrew Scheld have been using economic analyses to understand how fishermen’s preferences impact fish stocks – and conversely, how different aspects of the fishery impact fishermen’s wellbeing. Their work has provided managers with valuable insight for recognising best practices for bluefin tuna management.

Sustainable Management

Dr Scheld and Dr Goldsmith’s research investigates how sustainable management of the Atlantic bluefin tuna can be enhanced by better understanding the motivations underlying fishermen’s behaviour. Their research focuses on understanding factors that drive harvests by private recreational anglers and charter captains. They also examine how to promote the wellbeing of fishermen in this highly regarded fishery.

It is possible to quantify the economic impact of recreational fishing, estimating how much money is spent by fishermen on fishing-related activities. However, it is much more difficult to quantify the welfare benefits that the bluefin tuna fishery provides to fishermen and identify the specific parts of the fishing experience that provide the most happiness to participants. ‘Understanding how fishermen value different aspects of the fishing experience improves predictions of fishing behaviour and also enables managers to consider fishermen welfare when setting regulations,’ emphasises Dr Scheld.

Funded by a National Marine Fisheries Service (NMFS) Saltonstall-Kennedy grant and a National Marine Fisheries Service-Sea Grant Fellowship, Dr Scheld and Dr Goldsmith have used diverse methods and outreach to understand what motivates recreational anglers. Some of their work has already been published in the scientific literature. Because of the nature of their study design, surveying anglers across a large coastal area, they engaged in extensive outreach through a number of means, including *On The Water* Magazine, which helped improve awareness of the study and garner support from the fishing community.

The team used quantitative approaches, grounded in resource economics, to answer questions that are essential to the conservation of this highly coveted species. Their unique approach to interpreting the behaviour and response of Atlantic bluefin tuna fishermen offers a novel perspective to help address a long-standing fishery management issue.

Fishermen Welfare

To understand the motivations of Atlantic bluefin tuna fishermen, Dr Goldsmith and Dr Scheld surveyed over 5,000 bluefin tuna fishermen from Maine to North Carolina in the spring of 2016, separately questioning private and charter captains. The questionnaires used ‘mock fishing trip scenarios’ – hypothetical fishing trips described in detail to tease out which attributes within a fishing outing were most relevant to the welfare of the respondents. In choosing their most

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preferred trip scenarios – consisting of trip attributes such as the number of fish caught, the size of the fish caught, the number of fish kept, and cost – respondents implicitly provided information regarding what factors most affected their enjoyment of fishing trips.

The team then used econometric models – statistical models that reveal economic relationships – to understand these preferences. Dr Goldsmith and Dr Scheld were particularly interested in understanding the differences in interests and preferences among fishermen and how the 'motivations change according to the characteristics of the individual,' explains Dr Goldsmith.

Recreational anglers fell into two major groups: those that relished the experience of being out on the water regardless of what they caught or harvested that day, and those whose enjoyment of the fishing experience was almost exclusively dictated by how many fish they harvested. Interestingly, the former category primarily comprised anglers with higher incomes and those who had recently fished for bluefin tuna.

Using model results coupled with fishery data on number of trips, costs and catch rates, Dr Goldsmith and Dr Scheld were also able to quantify the benefits gained by fishery participants. 'We estimated that the overall value derived by anglers in the fishery (above and beyond their expenditures) was about $14 million in 2015,' notes Dr Scheld.

Predicting recreational Atlantic bluefin tuna catches has been a longstanding issue for managers tasked with ensuring that the United States does not catch more than its internationally allocated quota. 'Because of the very large number of potential recreational anglers, subtle changes in bluefin availability or regulations can result in greatly increased catches,' says Dr John Graves, an expert on bluefin tuna biology and management also from the Virginia Institute of Marine Science and a key collaborator on this study. 'High catch rates could cause the US to exceed its annual bluefin quota, reducing quotas and fishing opportunities in future years.'

This risk of exceeding allowable limits results from shifts in fish availability and uncertainty in predicting the annual effort and harvest of fishermen, coupled with the challenge of monitoring catches in near real-time. By working with the fishing community to quantify the motivations of anglers, Dr Scheld and Dr Goldsmith have provided a unique and valuable perspective on this complex issue with data that were previously unattainable.

Uncertainty Across Sectors

A related study spearheaded by Dr Goldsmith and Dr Scheld examined the most significant factors that influence whether a fish is kept or released once it has been caught by a charter captain, who, unlike a recreational angler, is permitted to harvest a fish either for commercial sale or for personal (or charter customer) consumption.

After analysing the questionnaires, the team found that harvest decisions varied greatly from captain to captain. However, individual characteristics, such as region and previous fishing behaviour, coupled with characteristics of the fishing trip, such as whether paying charter customers were on board, regulations, and anticipated fish size, strongly influenced harvest decisions. Dr Goldsmith emphasises that 'these findings can be used by managers to better predict harvest patterns under changing fishery conditions for this specialised fishing sector.'

Although determining fishermen's attitudes and motivations can be difficult, understanding what drives behaviour is crucial to ensure that the benefits of the fishery are being maximised while promoting sustainable harvest levels. By bridging the gaps between scientists, managers and fishermen, Dr Scheld and Dr Goldsmith have provided bluefin tuna fishery participants across sectors answers to nuanced and necessary questions. Such answers are highly relevant for managing the species and sport.

Meet the researchers

Dr Andrew Scheld
Virginia Institute of Marine Science
College of William & Mary
Gloucester Point, VA
USA

Dr Andrew Scheld is an Assistant Professor of Marine Science in the Department of Fisheries Science at the Virginia Institute of Marine Science, College of William & Mary. His research focuses on the economics of fisheries management, developing and applying quantitative models to analyse fisheries policies in the US and abroad. He completed his PhD in Fisheries Sciences at the University of Washington in 2014, after studying Environmental and Natural Resource Economics for both his Bachelor's and Master's degrees at the University of Massachusetts and the University of Rhode Island, respectively.

CONTACT

E: scheld@vims.edu
W: http://www.vims.edu/people/scheld_a/index.php

Dr William Goldsmith
1001 F St. NE
Washington, DC
USA

Dr William Goldsmith completed his PhD in Marine Science at the Virginia Institute of Marine Science, College of William & Mary, in January 2018. His dissertation focused on characterising the biological impacts and human dimensions of the recreational fishery for Atlantic bluefin tuna along the east coast of the United States. He is currently a National Oceanic and Atmospheric Administration (NOAA) Sea Grant Knauss Marine Policy Fellow in the office of US Senator Ed Markey (D-Mass), where he works on a broad range of energy and environment issues. A passionate recreational angler, Dr Goldsmith is interested in crafting collaborative, multidisciplinary approaches to solving complex fisheries problems.

CONTACT

E: william.m.goldsmith@gmail.com

KEY COLLABORATORS

Dr John Graves, College of William & Mary
Dr Clifford Hutt, Brad McHale and Sarah McLaughlin, NOAA
Dr Ron Salz, NOAA
Dr Kristy Wallmo, NOAA
Quantech, Inc., Rockville, MD, USA
On The Water Magazine, East Falmouth, MA, USA
Dr Rob Hicks, College of William & Mary
Dr Deb Steinberg, College of William & Mary
33 bluefin tuna fishermen who participated in focus groups in North Carolina, New Jersey, and Massachusetts

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FURTHER READING

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AFCERC: THE AGRIBUSINESS, FOOD & CONSUMER ECONOMICS RESEARCH CENTER

Research investigating the economic, social, psychological and physiological factors that influence consumers' food choices can help in gaining a better understanding of how individuals select particular foods. The Agribusiness, Food, and Consumer Economics Research Center (AFCERC) at Texas A&M University addresses practical problems affecting the agribusiness community, both domestically and globally. AFCERC researchers provide analyses, strategic planning, business analytics, and forecasts of market conditions that impact US and international agricultural and food industries.

Understanding Consumer Food Choices

Obesity is one of the most pressing health issues in the United States as well as in many other countries worldwide. Around two-thirds of the US adult population is currently overweight or obese, in addition to a growing number of children and adolescents. Being overweight and obese can increase the risk of developing a series of severe conditions, including cardiovascular diseases, strokes, high blood pressure, diabetes, and cancer.

In addition to environmental, genetic and lifestyle-related factors, this upsurge in obesity rates might also be caused by the consumption of unhealthy food and beverages. A number of researchers argue that the high obesity rates in the United States are associated with increases in the consumption of sugar-sweetened beverages and snacks. As a result, some policymakers have suggested increased taxes on these products. The American Beverage Association opposes this idea, arguing that obesity is a very complex problem that should be addressed with a comprehensive plan, educating the population on nutrition.

An effective solution to tackle the issue of obesity has yet to be devised. Therefore, research exploring the mechanisms behind consumer choices is of key importance, as it could inform policy makers and industry groups on how to best promote the consumption of healthier food products without hindering the economy.

It is therefore of crucial importance for researchers to gain a better understanding of the economic, social, psychological and physiological factors that lead individuals to select particular products. Food consumption and the nutritional quality of people's diets are jointly determined by income, prices, advertising, and a variety of other factors. Research studies that investigate the impact of these elements could ultimately lead to more effective agricultural and food policies that best allocate resources to ensure a safer, affordable and nutritious food supply.

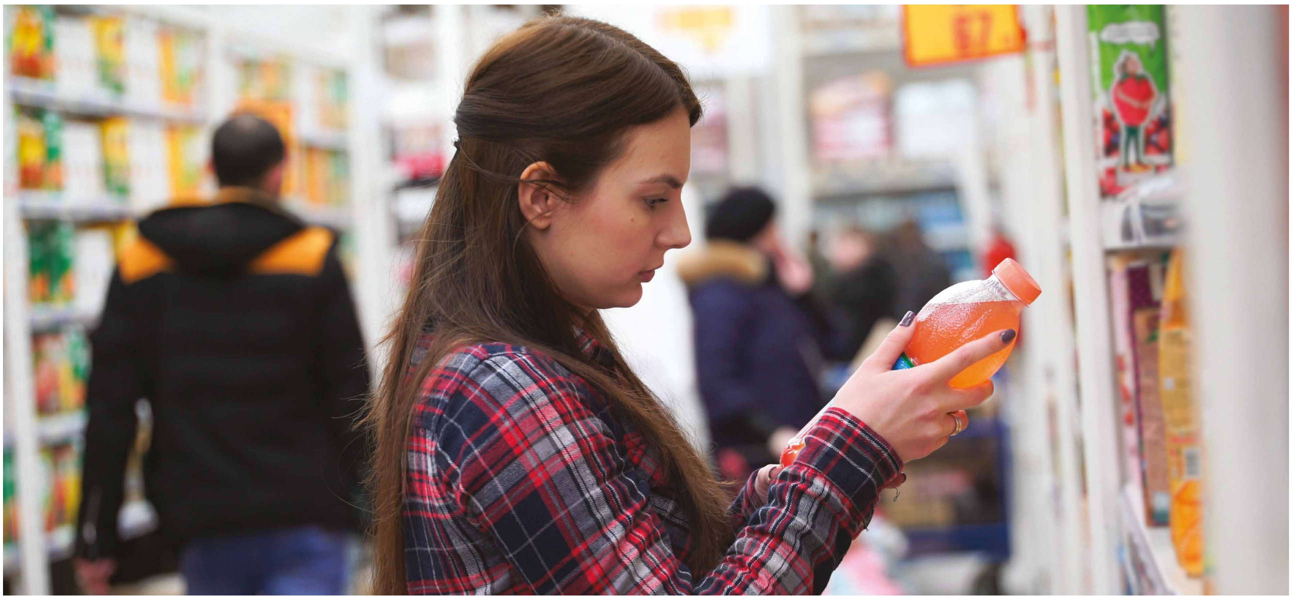
The Agribusiness, Food, and Consumer Economics Research Center (AFCERC) at Texas A&M University carries out research into the agricultural, agribusiness and food industries. The aim of this research is to provide input

to improve strategic decision-making at all levels of the food and drink supply chain, from producers to processors, wholesalers, retailers and consumers.

AFCERC's Mission

AFCERC is a research and outreach organisation of Texas A&M AgriLife Research and is part of the Department of Agricultural Economics at Texas A&M University. The Center was first established as a market research service of the Texas Experiment Station and the Texas Extension Service in 1969, under the name of the Texas Agricultural Market Research and Development

‘Our prominent projects deal with consumer demand analyses of various products, particularly dairy products and non-alcoholic beverages as well as evaluations of the effectiveness of commodity checkoff programs.’



Center. After 1988, it became known as the Texas Agribusiness Market Research Center, and a formal change to its current name was approved in 2010.

The faculty members who are primarily responsible for the Center’s day-to-day operations include Dr Gary W. Williams, Dr Oral Capps, Jr, and Dr Victoria S. Salin, but the AFCERC team also consists of a number of other professional researchers and associates.

AFCERC’s main mission is to carry out timely, high-quality, and objective research that could support policy-makers and industry experts in their decision-making process, helping them to devise informed and effective strategies. The Center also provides analyses, strategic planning, business analytics, and forecasts of market conditions impacting both US and global agricultural, agribusiness and food industries. The Center’s main topics of interest can be divided into three categories: agribusiness and markets, health and nutrition, and consumer research.

AFCERC’s studies in agribusiness and markets explore aspects such as logistics, distribution, concentration, industrialisation, strategic management and pricing strategies. Additionally, attention is devoted to evaluations of the effectiveness of agricultural checkoff programs mandated by the U.S. Congress. In the area of health and nutrition, AFCERC researchers place a particular focus on obesity and its associated factors, as well as issues concerning food safety, child nutrition and public interest such as proposed taxes on sugar-sweetened beverages, proposed changes in the Special Supplemental Nutrition Program for Women, Infants, and Children (WIC), and the economic and social costs associated with mislabelling food and beverage products. Finally, the Center also conducts extensive consumer research focusing on areas related to dairy products, beverage products, the purchase patterns of consumers according to various socio-demographic profiles, food safety, and food advertising and promotion programs.

‘While we do work on many facets of research, our prominent projects deal with consumer demand analyses of various products, particularly dairy products and non-alcoholic beverages as well as evaluations of the effectiveness of commodity checkoff programs (advertising and promotion programs for various agricultural commodities),’ explains Dr Capps.

AFCERC has a number of important domestic and International clients, including various agricultural commodity Boards (notably the Cotton Board, the United Soybean Board, and Dairy Management, Inc), the Kellogg Company, Dow Chemical Company, John Deere, the Norwegian Seafood Council, and countless other groups.

Research Projects

The research and outreach programs carried out by AFCERC are primarily aimed at exploring challenges related with encouraging healthier food consumption while also growing the economy. Key findings are then disseminated among policy makers, agricultural producers, processors, commodity organisations, rural communities, food industries, government agencies, and other important stakeholders.

The team provides quantitative/statistical analyses based on data gathered from Information Resources, Inc. (IRI), Nielsen, the NPD Group, Inc. (NPD), the United States Department of Agriculture (USDA), and various other organisations. Spanning across a wide variety of topics, AFCERC's research includes studies of the drivers for demand of food products, catering to time-starved as well as health-conscious consumers, ascertaining the effectiveness and effects of food advertising, assessing the impacts of food safety, understanding consumption patterns of particular socio-demographic groups, and much more.

To assess the possible benefits and limitations of taxing sugar-sweetened beverages, analysts at the Center have carried out extensive research into these products. Their analyses suggest that decreases in consumption of sugar-sweetened beverages would be relatively small as a result of the proposed taxes, while market revenues would diminish substantially. These studies highlighted the need to consider demand interrelationships among various non-alcoholic beverages, not just sugar-sweetened beverages, particularly when assessing the effects of tax strategies. The researchers involved also suggested that imposing a tax on sugar-sweetened beverages may not be a very effective way to alleviate U.S. obesity rates.

Another example of research carried out by AFCERC is a thorough analysis of the energy drinks market. For this investigation, researchers gathered information from a retailer located near the Texas A&M campus to estimate demand relationships for major energy drinks brands.

AFCERC researchers are also carrying out demand analyses for milk, organic milk, and dairy-alternative beverages in the United States. Their aim is to identify factors that might affect the volume of these beverages purchased, calculating own-price, cross-price, and income elasticities for dairy products and non-dairy alternatives, and suggesting possible retail-pricing strategies.

In terms of research investigating the effects of advertising and promotion, one of AFCERC's recent studies assessed the impact of support programs run by agricultural promotion groups. The study in question evaluated 27 major generic advertisement programs aimed at promoting the economic welfare of agricultural producers by financing activities that could increase demands for their commodities.

The research team concluded that these programs have actively enhanced profits of associated stakeholders, initiating important multiplier effects through the economy as well as generating notable rates of returns, new jobs, and greater income.

Market Analyses and Consumer Research

The eating and drinking habits of human beings have continuously evolved throughout history, affected by a multitude of economic, social, environmental, psychological and physiological factors. In recent years, the significant rise in US obesity rates, with all associated health issues, has highlighted the need to better understand the mechanisms behind consumer choices, in order to devise effective ways to encourage the consumption of healthier foods without damaging the industry.

Research and outreach initiatives carried out by AFCERC have contributed to informing government agencies as well as other organisations operating in the agricultural, agribusiness, and food industries about important areas of the food and drink economy.

Through its many research studies and industry collaborations, AFCERC has become a leading source of knowledge on the process by which food reaches consumers and on what products could positively contribute to the population's health and safety. AFCERC distinguishes itself from other domestic and international academic organisations through its research and services designed to address practical problems, use of state-of-the-art quantitative/statistical techniques, and development of partnerships within the private sector.

Market analyses, evaluations, and in-depth studies carried out by researchers at the Center have helped to better understand a variety of aspects related to the food and beverage industry. For instance, AFCERC's research has shed light on the dynamics behind product demand, assessed the possible consequences of taxing sugar-sweetened beverages, evaluated the effectiveness and the impacts of advertising and promotion initiatives, and helped to better understand price spreads of particular types of products.

The Center has also carried out studies that could help industry representatives to better understand food consumption patterns of particular demographic groups, such as low-income populations, adolescents, pre-adolescents, pre-school children, or elderly populations as well as Hispanic and Muslim populations.

Overall, AFCERC's work has led to the development and expansion of alternative methods of estimating demand relationships based largely on economic forces, socio-demographic factors, health, nutrition, and other elements associated with the food and beverage industry. To this end, this effort rests on the use of the best available data as well as state-of-the-art statistical techniques. 'The set of research ideas and their operationalization will ultimately translate into increased benefits to the food industry, both tangible and intangible,' says Dr Capps.

Meet the researchers

Dr Gary W. Williams
Co-Director and Chief Operating Officer
Agribusiness, Food, and Consumer Economics Research Center
Texas A&M University
College Station, TX
USA

Dr Gary W. Williams is Co-Director and Chief Operating Officer of AFCERC, responsible for managing the centre's research program. He holds a PhD and an MS in Agricultural Economics from Purdue University, as well as a BS in Economics from Brigham Young University. Dr Williams is also a Professor of Agricultural Economics at Texas A&M University. He previously worked as a Professor and Assistant Coordinator of the Meat Export Research Centre at Iowa State University, as Senior Economist at Chase Econometrics, and as an agricultural economist for the US Department of Agriculture. Dr Williams leads AFCERC projects related to commodity, agribusiness markets, trade, and policy.

CONTACT

E: gwwilliams@tamu.edu

Dr Oral Capps, Jr
Co-Director and Chief Resource Development Officer
Agribusiness, Food, and Consumer Economics Research Centre
Texas A&M University
College Station, TX
USA

Dr Oral Capps, Jr is Co-Director and Chief Resource Development Officer of AFCERC. He attained a PhD and an MS in Agricultural Economics, an MS in Statistics, and a BS in Mathematics from Virginia Tech. Dr Capps holds the Southwest Dairy Marketing Endowed Chair and is a Regents Professor of Texas A&M University. He is nationally and internationally recognised as a leader in demand analysis with particular expertise in econometric modelling and forecasting methods and has served on the Board of the Agricultural and Applied Economics Association, as well as being the past President of the Food Distribution Research Society. He leads AFCERC research programs related to food industry performance, pricing, and consumer behaviour.

CONTACT

E: ocapps@tamu.edu

Dr Victoria S. Salin
Co-Director and Chief Financial Officer
Agribusiness, Food, and Consumer Economics Research Center
Texas A&M University
College Station, TX
USA

Dr Victoria S. Salin is Co-Director and Chief Financial Officer of AFCERC, responsible for managing the centre's budget, staffing, and day-to-day operations. Dr Salin holds a BA in Political Science and History from Miami University and an MA in Government and Foreign Affairs from the University of Virginia. She was awarded her PhD from Purdue University in 1996, for a project focused on agribusiness finance and international trade. She is currently a Professor of Agricultural Economics at Texas A&M University, Chair of the Intercollegiate Faculty of Agribusiness, and Director of the Master of Agribusiness Program. She previously held positions in industry and at the US Department of Agriculture. She leads AFCERC projects related to food safety, traceability, logistics, and strategic management.

CONTACT

E: v-salin@tamu.edu

Loren N. Burns
Program Manager
Agribusiness, Food, and Consumer Economics Research Center
Texas A&M University
College Station, TX
USA

Loren N. Burns is the Program Manager of AFCERC at Texas A&M University. She received her BSc in Agribusiness with a Minor in Agricultural Economics from Texas A&M University. Burns is responsible for managing the day-to-day operations of the Center, as well as maintaining account records that include directing authorisation and allocation of funds. She interacts with external and prospective clients to successfully define parameters, transaction terms, and limitations surrounding research projects. She also edits and composes many different types of complex documents in addition to compiling and presenting periodic financial reports to meet the needs of the Department and University System. Prior to joining the Department of Agricultural Economics, Ms Burns was a Proposal Administrator at both the Texas A&M Research Foundation and the Texas A&M University System Sponsored Research Services.

CONTACT

E: lorenburns@tamu.edu