Scientia

CULTIVATING RESILIENT ECOSYSTEMS AND SUSTAINABLE FARMS

HIGHLIGHTS:
- How Ecosystems are Built: Competition and Cooperation in Evolution
- Planting Hedgerows to Boost Biodiversity and Protect Crops
- Integrating Sustainability with Productivity in Crop and Animal Farming
- Exploring How Fish Adapt to Climate Change

EXCLUSIVES:
- The European Society for Evolutionary Biology
- The European Society of Agricultural Engineers

Issue: #142

WELCOME...

Restoring Earth's ecosystems and ensuring global food security are two of the greatest challenges humanity has ever faced. These puzzles are even more challenging in the face of climate change and a growing human population. In this important issue of Scientia, we meet scientists who are tackling both of these challenges head on.

The first half of the issue showcases the work of ecologists and conservation scientists, whose research is informing new strategies to protect and restore Earth's precious biodiversity. We open this section by speaking with Professor Astrid Groot, President of The European Society for Evolutionary Biology, who explains how evolutionary insights are essential for devising effective conservation plans.

Next, we meet many fascinating scientists, each conducting important research in the areas of ecology or evolutionary biology – from identifying the best strategies to protect Louisiana's wetlands, to exploring how 'genetic rescue' can save inbred populations of animals and plants from extinction.

In the latter half of the edition, we feature numerous exciting research projects that attempt to future-proof our agricultural systems. From using satellite-based technologies to predict crop failures, to exploring how cover crops can sustainably improve soil health, the scientists featured here are ensuring our future food security, while safeguarding the natural environment.

Science Diffusion

CONTACT

Published in the UK, by Science Diffusion ltd

ISSN 2059-8971 (print)
ISSN 2059-898X (online)

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

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

Barrier Free

Meet The Team...

CONTENTS

ISSUE : #142

ECOLOGY & EVOLUTION

SUSTAINABLE FOOD SECURITY

ECOLOGY & EVOLUTION

THE EUROPEAN SOCIETY FOR EVOLUTIONARY BIOLOGY

Founded in 1987, the European Society for Evolutionary Biology (ESEB) is an academic society that brings together over 2000 biologists from Europe and beyond. In this exclusive interview, we speak with Professor Astrid Groot, President of ESEB, who discusses the many ways that the society supports scientists and helps to advance the diverse field of evolutionary biology.

To begin, please tell us a little bit about the history and mission of ESEB.

The European Society for Evolutionary Biology (ESEB) was founded by Stephen Stearns on 28 August 1987 in Basel, Switzerland, to provide a European focus, as the Society for the Study of Evolution was mainly US based. The founding of ESEB was closely linked to the launching of the Society's journal, the *Journal of Evolutionary Biology*.

ESEB aims to support the study of organic evolution, fosters exchange and communication within the evolution community, countering inequalities within the community, educating the public about evolution and why it is important, and lobbying decision makers to support evolutionary research and education. Beside publishing the *Journal of Evolutionary Biology and co-publishing Evolution Letters*, the society organises a biannual congress (see https://www.eseb2022.cz/en/symposia) and supports other events to promote advances in evolutionary biology.

ESEB also financially supports activities to promote a scientific view of organic evolution in research and education.

Who are your members, and what are their areas of expertise?

We have 99.99% researchers, of which about 50% are students and 50% post-PhD scientists. The research areas represented are very broad, ranging from evolutionary ecology to molecular evolution, and from plants and mites to mice.

For example, the organiser of this year's ESEB congress, Lukas Kratochvil, studies the evolution of sexual dimorphism, behaviour and reproductive biology in lizards, while last year's ESEB president Ophelie Ronce focuses mostly on plant communities and integrates ecological and evolutionary responses to climate change. The ESEB secretary Ellen Decaestecker investigates host-pathogen interactions in water fleas and spider mites, while ESEB treasurer Koen Verhoeven studies epigenetic variation in asexually reproducing dandelions. Finally, my research focuses on how evolution of sexual communication in moths affects speciation.

The list of 40 symposia at our upcoming ESEB congress in Prague also shows the breath of topics of our members, as this ranges from sex chromosome evolution, evolutionary ecology of mating systems, cognitive evolution and eco-evolutionary dynamics in invasive species to molecular evolution, evolution of antibiotic resistance and microbiomes in the wild.

In what ways does ESEB support research in evolution and related fields?

ESEB supports the publishing the society's journals, *Journal of Evolutionary Biology and Evolution Letters*. ESEB also organises the biannual ESEB congress and supports the yearly European meeting of PhD students in Evolutionary Biology (EMPSEB).

In addition, the society funds travel awards to the ESEB congress and the conferences of the Society for the Study of Evolution (see travel awards to ESEB and SSE congresses), mobility awards to visit labs or do fieldwork, special topic networks, and progress meetings. These funds are mostly to foster connections between evolutionary societies and communication with national evolutionary communities.

ESEB also promotes careers and highlights research of evolutionary biologists by awarding prizes, such as the Stearns Graduate Student Prize for best student paper, the John Maynard Smith Prize for early career researchers, the Presidents' award for mid-career scientists, and the Distinguished Fellows award for senior researchers.

This August, the ESEB 2022 Congress will be held in Prague. When thinking about this upcoming event, what are you most excited about?

After two years of online conferences and meetings, I'm mostly excited to see everyone in person again and to be able to interact with people not only through presentations with related discussions, but also by having coffee, drinks and dinner together and meeting each other randomly in the hallways, as collaborations frequently start in these informal settings.

Also, live meetings give the opportunity to hear talks that I would probably not choose to listen to online. For example, at the last live ESEB meeting I was tired of moving between rooms at one point and then heard an amazing talk on tRNA evolution that I would have missed otherwise, which led to a new collaboration.

Tell us a bit more about ESEB's efforts in public outreach and education, such as the Outreach Initiative Fund and Evolution Matters. Why is outreach particularly important in evolutionary biology and related fields?

The Outreach Initiative is one of the oldest and most successful initiative of ESEB. We find it crucially important to ensure that evolution is generally accepted in all communities and societies, including religious ones. One great example of an ESEB outreach initiative is the EvoKE project, which stands for Evolutionary Knowledge for Everyone. The EvoKE project 'seeks to contribute to a world where people understand evolution and can use scientific knowledge and skills to make informed decisions that address societal problems, thereby contributing to an inclusive, sustainable and resilient future.'

This project consists not only of researchers, but also educators, journalists, communicators and artists, who all actively reach out to promote evolution at all levels of our society and to help for example educators and policy makers to understand what evolution is and is not.

Education is important, because evolution is a fundamental scientific principle that governs the natural world and impacts the human condition. The coronavirus outbreak clearly showed that we humans are part of the network and evolution of life.

CREDIT: Laila Kee

Other obvious examples are antibiotic resistance and resistance to insecticides.

Basically, evolution describes change through time, where time is measured in generations instead of years. We need to promote research and factual discourse and counter pressure against science, such as from creationists.

Evolution does not contradict or oppose religious views; in fact, several great evolutionary biologists were and are religious. For example, the author of the famous expression 'Nothing in biology makes sense, except in the light of evolution', Dobzhansky, was a theist who saw the Bible and the Koran not as primers for natural science, but as the 'meaning of man and his relations to God'.

Evolution is also not 'just a theory or opinion', but a fact of life just like gravity. Especially in these polarising times, communication between different groups of people is so important on many different levels: within our own species, to stop prejudice, which are the basis of many unnecessary wars and fights, and for all other species with which we share this planet and without which we cannot live.

Finally, we are now in the midst of Earth's sixth mass extinction event. Why is the field of evolutionary biology so important for mitigating this crisis?

Climate change and human impact have major impacts on pretty much all life on the planet, on land and in water. Not only changes in temperature and rainfall patterns, but also light, acoustic and chemical pollution, affect interactions between individuals within and between populations and species in all ecosystems. In turn, ecosystems are affected by species interactions and distributions.

For example, crops and grazing land now cover more than 30% of all land on Earth, while intensive agricultural practices and overgrazing are among the major causes of desertification. By analysing how genetic diversity within species affect various factors such as drought resistance or susceptibility to viruses, and how interactions between species affect food webs aboveground and belowground over time, evolutionary biologists can help policy and management plans to mitigate overexploitation and desertification.

Also, invasive plant, insect, fish, bird, parasite and predator species profoundly affect the ecology and evolution of all species with which these species interact. As invasive and native species have not co-evolved, premating barriers may not exist, so that unexpected hybridisations may occur. Evolutionary biologists can predict the likelihood and impact of such events.

Evolutionary insights are also crucial for conservation measures of endangered species, the success of which depends on population sizes and possible gene flow between populations, because these affect the genetic variation, the level of inbreeding and viability of species.

https://eseb.org/society/

UNRAVELLING A BIOLOGICAL MYSTERY: WHY WE INHERIT MORE MATERNAL DNA

Around 1.5 billion years ago, our single-celled ancestor had a fateful snack – it engulfed another bacterium. The engulfed organism initially lived within the other, but slowly transformed over generations to give rise to mitochondria – an important organelle found in the cells of Eukaryotes. Interestingly, mitochondria have DNA that is passed exclusively from one parent onto their offspring. In most organisms, including us, that parent is the mother. Why we only inherent maternal mitochondrial DNA is one of the oldest unanswered questions in evolutionary biology. **Dr Madeleine Beekman** of the University of Sydney has explored this topic deeply, proposing new theories to explain why we are more related to our mother than our father.

Mitochondria Power Life

During sexual reproduction, an offspring receives two genomes: DNA within the nucleus, and DNA within organelles in the cytoplasm – the gelatinous liquid that fills the cell. Cytoplasmic genomes include DNA in mitochondria and the chloroplasts of plant cells.

Mitochondria generate the chemical energy needed to power every cell in the human body. The energy is stored in a complex molecule termed ATP – life's common energy currency. Not surprisingly, mitochondria are found in all human cells, with particularly large numbers in tissues that require a lot of energy, such as muscles and the brain.

Each mitochondrion contains multiple copies of its DNA. While the father's and mother's nuclear genomes recombine during sexual reproduction, mitochondrial DNA comes exclusively from the mother – meaning that mitochondria reproduce asexually.

In fact, in mammals, sperm cells deliberately tag their mitochondrial DNA for destruction after fertilisation. Maternal inheritance of mitochondrial DNA is one of the most preserved biological patterns we have, and is consistent across almost all lifeforms.

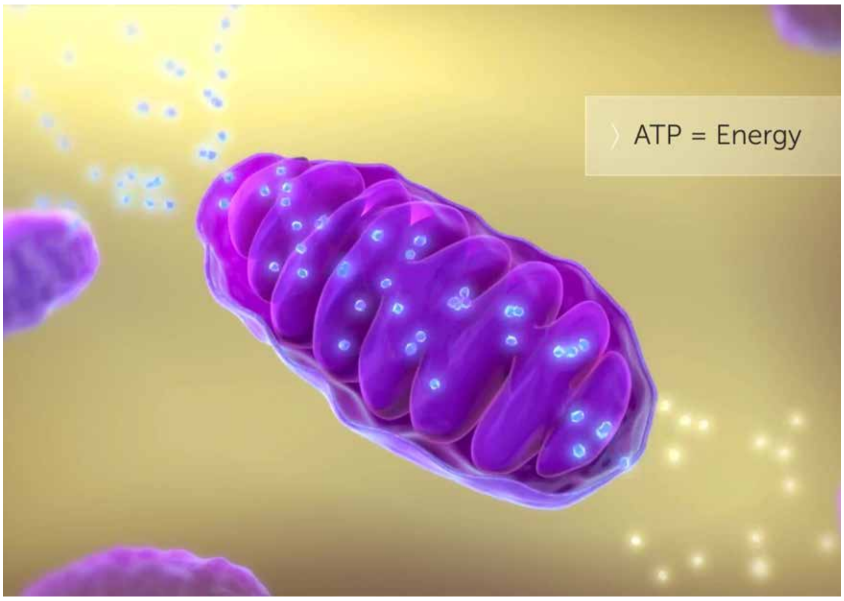
Some exceptions to the rule of 'uniparental' inheritance include baker's yeast and some male bivalves. However, in both cases, the mitochondrial DNA from the mother and father are segregated. For example, in bivalves, the father's mitochondrial DNA appears only in the reproductive organs of male offspring, while the mother's mitochondrial DNA is found in all other cells in the offspring's body, including in the reproductive tissues of her daughters.

A trend that has persisted for so long, across so many species, must be favourable for the persistence of life. However, we still lack a theory explaining maternal inheritance supported by scientific data. Dr Madeleine Beekman of the University of Sydney has been at the forefront of this research for years. Her most recent work examines maternal inheritance as a potential answer to another biological mystery: how have asexual genomes, such as mitochondrial DNA, undergone adaptive evolution without sex? While she had been pondering the mystery of uniparental inheritance and the mitochondrion's ability to evolve without sex, it was not until Joshua Christie joined her as a PhD student that she started to find the answers.

Avoiding Genetic Conflict

The most common hypothesis used to explain maternal inheritance of mitochondrial DNA is called conflict theory. The idea is that replicating mitochondrial DNA quickly is at odds with the organism's best interest.

Like all genetic beings, mitochondria 'want' to replicate quickly; such fast-



replicating mitochondria are known as 'selfish' mitochondria amongst biologists. However, rapid replication can be sloppy. With each round of replication, mistakes can be made and mutations arise. So, the more replications, the higher the chances are that things will go wrong. Because mitochondria are essential for the creation of cellular energy, sloppy replication can negatively impact the cell, and therefore the whole organism.

Conflict theory suggests that inheriting mitochondria from both the mother and father will facilitate the spread of selfish mitochondria. When both parents pass on their mitochondria, each offspring will contain a genetic mixture in their cells. Such a mixture would set the scene for these genetically different mitochondria to compete with each other over who can replicate the fastest. To avoid such conflict, natural selection – which acts more on the whole organism than on individual mitochondria – has led to the uniparental inheritance of mitochondrial DNA. In most organisms, the parent that is the sole transmitter is the mother; but it could easily have been the father. Conflict theory has been the predominant explanation of uniparental inheritance for nearly three decades, but we have no evidence – either from models or real data – to back it up.

Another theory poses a more straightforward solution: has maternal inheritance evolved because carrying multiple mitochondrial types imposes a cost on the organism? Dr Beekman and Joshua, now Dr Christie, used a mathematical model to explore whether natural selection against heteroplasmy – a state of having multiple mitochondrial genomes – could lead to the evolution of uniparental inheritance.

A New Theory

All DNA is vulnerable to mutations. Mutations are important as they allow new traits to arise. In fact, if an entity only reproduces asexually, as mitochondria do, then mutations are particularly important, since they are the only way that the genome structure can change. During sexual reproduction, new genetic combinations are formed by the mixing of maternal and paternal genomes, but this is not the case in asexual reproduction.

Dr Beekman, Dr Christie and the applied mathematician Tim Schaerf wanted to know whether maternal inheritance would constantly beat biparental inheritance in an evolutionary arms race, or whether a predominance of one type of mutation – neutral, beneficial, or harmful – would tip the scale in favour of one strategy for the other.

They created a mathematical model of the evolution of a free-living eukaryotic organism. Almost all eukaryotic organisms, including animals, plants and fungi, contain mitochondria in their cells. The team's model manipulated genetic mutations in the mitochondria to be neutral, beneficial, or harmful. They then monitored the distribution of cell types in each scenario. For each type of mutation, they ran the model over multiple generations to see if uniparental inheritance would ever evolve from the ancestral state of biparental inheritance.

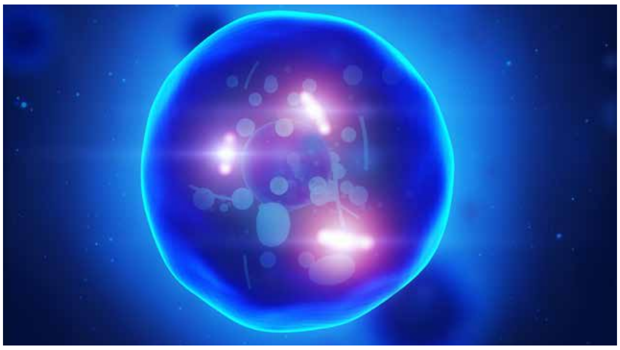
Maternal inheritance of mitochondrial DNA replaced biparental inheritance under all scenarios. The team's results also explained many exceptions to strict maternal inheritance, such as those observed in yeast and bivalves.

Furthermore, the team's model results also explain observations from a biological study in which mice were modified so that their cells contained two different mitochondrial genomes. While mice with one mitochondrial genome were normal, those with two suffered physiological impairments, including compromised respiration and reduced cognition.

Although the cost of having multiple copies of mitochondrial DNA now has a solid theoretical foundation and some empirical support, scientists still don't understand the underlying mechanisms. Dr Beekman stresses that we need more data on various organisms to support or refute the model.

Asexual Genomes and Muller's Ratchet

Sexual reproduction combines genes quickly, creating new genetic combinations, but it also allows beneficial mutations to spread more quickly and for deleterious ones to be removed. Beneficial mutations help the organism to more successfully survive and reproduce; thus, natural selection favours their persistence from



generation to generation. Harmful mutations, on the other hand, can be removed during sexual reproduction, and so do not accumulate to levels within a population that could lead to that population's extinction.

In contrast, genomes that reproduce asexually, can only create or remove mutations through errors in genome replication, which are rare and random. Thus, harmful mutations can accumulate rapidly and unavoidably, an effect known as 'Muller's ratchet'. In theory, this should lead to the irreparable meltdown of asexual genomes over many generations.

Despite the disadvantages, asexual reproduction offers many benefits, including a quicker reproduction rate that is not dependent on the availability of a sexual partner. Indeed, there are many examples of asexual organisms that have persisted for a long time. Long-lived asexual populations have evolved strategies for getting around the costs of asexual reproduction, such as very large population sizes and the occasional sexual exchange. However, mitochondria are in a different scenario: their population sizes are so small that models suggest they should struggle to accumulate beneficial mutations and purge deleterious ones. In fact, the mitochondrial genome should no longer exist.

We need look no further than the mammalian Y chromosome to see the consequences of a lack of sex. Like mitochondrial DNA, the Y chromosome is only transmitted from one parent – this time only from father to son. The Y chromosome has tell-tale signs of the effects of Muller's ratchet: it is so small that, if the deletion rate continues, the Y chromosome – and the male sex – will disappear within the next 10 million years. In fact, parts of the degenerate human Y have already caused problems, such as low sperm viability.

On the other hand, mitochondrial DNA, which has been around much longer than the mammalian Y chromosome, doesn't show nearly as many signs of the costs associated with an asexual genome. What do the mitochondria have that the Y chromosome doesn't?

Intrigued by this evolutionary puzzle, Dr Beekman and Dr Christie wondered how to reconcile our fundamental theories of the costs of asexual reproduction with the evidence that mitochondrial DNA is somehow circumventing Muller's ratchet.

How Do Asexual Genomes Evolve?

Dr Beekman and Dr Christie created a model to determine how inheritance type (biparental or uniparental) and genome size affect the accumulation of beneficial and harmful mutations. They also modelled the rate of adaptive evolution – the propagation of beneficial mutations over deleterious ones.

The model reconciled the theory with observations, showing that the specific biology of mitochondrial genomes, asexual reproduction, uniparental inheritance and small population size, increases the efficiency of natural selection in a manner that compensates for the costs of asexuality.

The key to Beekman and Christie's theory is that selection can act on mitochondria on multiple levels: between the host cells carrying the mitochondrial DNA, and within the mitochondrial genomes themselves. When between-cell selection is stronger than within-cell selection, there is more variation upon which natural selection can act and more opportunities to purge deleterious mutations. Maternal inheritance, the researchers contend, increases between-cell choice and allows for greater adaptive evolution.

The number of mitochondria also matters. Because mitochondria are divided all over a mother's egg cells, each egg differs slightly in its mitochondrial DNA and eggs of poor quality, those that contain too many mutated mitochondria, are removed.

Their work suggests that mitochondria can enjoy the benefits of asexual reproduction while using maternal inheritance to mitigate the costs. A win-win situation and a solid explanation for why the mitochondrial genome is still going strong after more than two billion years.

Testing the Theory of Multilevel Selection

In a new project, Dr Beekman is putting her model of adaptive evolution in mitochondria to the test. Using a slime mould and a fungus as model organisms, Dr Beekman plans to experimentally manipulate the relative strength of mitochondrial DNA mutation types fundamental to her theory. At the end of this ongoing project, she will demonstrate whether maternal inheritance improves the mechanisms allowing for adaptive evolution in mitochondria.

By connecting the dots between theory and reality with empirical studies, Dr Beekman is shedding new light on some of biology's longest-standing questions. It's not just for curiosity's sake, either: understanding the selection of mitochondria will allow us to better treat numerous debilitating mitochondrial disorders, which affect millions of people across the globe.

Meet the researcher

Dr Madeleine Beekman
School of Life and Environmental Sciences
The University of Sydney
Sydney
Australia

In the early 2000s, Dr Madeleine Beekman found herself in South Africa studying the Cape honeybee. She fell in love with these curious insects, and since then, has spent decades studying social insect behaviour and theoretical evolutionary biology. Dr Beekman earned her PhD in Population Biology from the University of Amsterdam. After a brief period working outside of academia, she accepted a postdoctoral position at the University of Sheffield. In 2001, she started at the University of Sydney, where she would eventually become Deputy Head in the School of Life and Environmental Sciences and Professor of Evolutionary Biology. With more than 150 publications to her name, Dr Beekman is an impressive scientist with far-reaching contributions to evolutionary biology. In 2021, she switched her focus from teaching to popular science writing but is still connected to the University as Professor Emerita.

CONTACT

E: madeleine.beekman@sydney.edu.au
W: https://www.sydney.edu.au/science/about/our-people/academic-staff/madeleine-beekman.html

FUNDING

Australian Research Council

KEY COLLABORATORS

Joshua R. Christie, University of Sydney
Duur K. Aanen, Wageningen University
Johannes N. Spelbrink, Radboud University Medical Centre
Damian K. Dowling, Monash University
Timothy M. Schaerf, University of New England

FURTHER READING

JR Christie, M Beekman, Selective sweeps of mitochondrial DNA can drive the evolution of uniparental inheritance, Evolution, 2017, 71, 2090.

JR Christie, M Beekman, Uniparental inheritance promotes adaptive evolution in cytoplasmic genomes, Molecular Biology and Evolution, 2017, 34, 677.

JR Christie, M Beekman, Selective sweeps of mitochondrial DNA can drive the evolution of uniparental inheritance, Evolution, 2017,71:2090-2099.

JR Christie, M Beekman, Uniparental inheritance promotes adaptive evolution in cytoplasmic genomes, Molecular Biology and Evolution, 2017, 34, 677.

DK Aanen, JN Spelbrink, M Beekman, What cost mitochondria? The maintenance of functional mitochondrial DNA within and across generations, Philosophical Transactions of the Royal Society of London, 2014, 369, doi: 10.1098/rstb.2013.0438.

M Beekman, DK Dowling, DK Aanen, The costs of being male: are there sex-specific effects of uniparental mitochondrial inheritance?, Philosophical Transactions of the Royal Society of London, 2014, DOI: 10.1098/rstb.2013.0440.

JR Christie, TM Schaerf, M Beekman, Selection against heteroplasmy explains the evolution of uniparental inheritance of mitochondria, PLoS Genetics, 2015, DOI: 10.1371/journal.pgen.1005112.

HOW ECOSYSTEMS ARE BUILT: COMPETITION AND COOPERATION IN EVOLUTION

Despite the old adage 'nice guys finish last', cooperation is common in life – from the scale of genes or cells through to entire societies. Although these two ideas seem to contradict each other, **Dr Egbert Giles Leigh Jr** has demonstrated throughout his career at the Smithsonian Tropical Research Institute in Panama that working together has been the key to the success of multicellular life. Here, he explains his view of how competition and cooperation both played essential roles in bringing forth productive, diverse ecosystems.

The Benefit of Cooperation

Ever since philosophers have been considering the human condition, people have wondered about the origin and persistence of cooperative behaviour. If the imperative to survive and reproduce is 'selfish', why do we see so many examples of altruism and cooperation in both human and non-human societies?

The ancient Greek philosopher Plato remarked that even a gang of thieves – living by stealing from others – would need to be just, supportive and loyal to one another, or they would all fail to survive, let alone prosper. Similarly, members of Charles Darwin's hypothetical tribe of hunter-gatherers had to cooperate and treat each other fairly to defend themselves and their resources successfully against other tribes. It follows, he argued, that a greater proportion of courageous, loyal and cooperative members would give these tribes a distinct advantage over other tribes.

Courageous tribe members, however, die soonest, while shirkers live longer, with more time to have children – an example of how helping one's group reduces one's reproduction relative to other group members. Darwin argued, however, that courage also gives one a good reputation, which attracts defenders, a larger share of food, and other benefits from fellow tribe members that enable faster reproduction before death. Recently, Christopher Boehm found that courageous cooperation among tribe members is essential primarily for killing big game, and that communal punishment of cheaters who try to hog an excessive share of food or authority is also needed to ensure cooperation. But Darwin found the right approach to how morality evolved.

'Cooperative endeavour is as essential to the productivity and diversity of ways of life in natural ecosystems, as it is to human economies,' says Egbert Leigh. 'As competition in human economies causes people to cooperate so as to compete better with third parties, in nature competition often selects for social cooperation among members of the same species, and 'mutualism' – cooperation among members of different species – to compete better with others.'

Leigh has spent decades reflecting on the role of cooperation in evolution. He suggests that competition, rather than favouring selfish behaviour, can promote cooperative behaviours and lead to the complexity, harmony and beauty we see in nature today.

Genomes: Societies of Genes

In societies, each person is an individual whose survival and prosperity depends on other members of the society. In *The Theory of Moral Sentiments*, Adam Smith suggests that competition benefits society only when it is fair, so its members suppress unfair competition. Leigh explains that there are parallel patterns within our own genome, which can be viewed as a society of genes where natural selection acting on individual genes (the units) can give rise to fair competition among them. 'Genes are selfish, but they are interdependent: a gene only gets reproduced if the others do their jobs,' Leigh says.

Diploid parents, which have two exemplars of each gene, produce haploid eggs or sperm, which have one of each gene. For the two exemplars of each gene in the parent's genome, a lottery determines which is chosen to enter a given egg or sperm. If the lottery is fair, giving each gene an equal chance of being chosen, natural selection favours a gene only if it enhances the survival or reproduction of the individual carrying it. If a defective gene spreads by somehow biassing this lottery in its own favour, natural selection favours genes elsewhere in the genome that restores fairness. Here a 'moral' rule evolved without consciousness. This rule enabled natural selection to favour adapted individuals.

Building Complex Organisms

J. B. S. Haldane and Julian Huxley remarked that evolutionary progress – from the simple life that originated in deep-sea vents through to entire ecosystems of complex and sentient multicellular organisms – has been driven by two main processes: 'individuation' and 'aggregation'. Individuation is the evolution of a unit step by step under natural selection to become better adapted. Aggregation occurs when separate units join together to form a super-unit. In a super-unit formed by aggregation of identical units, the units may differentiate in accord with the demands of division of labour, transforming the super-unit into an individual in its own right.

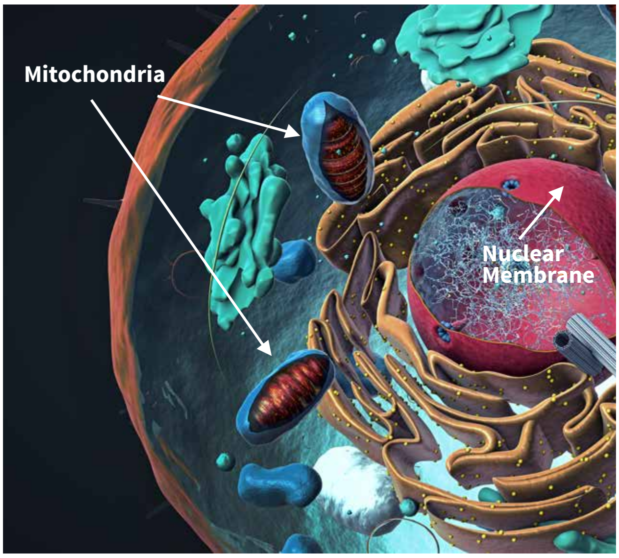
Combining units of different types is another way to make super-units. Complex multicellular organisms would not exist today if not for an early instance of aggregation and cooperation. Around two billion years ago, a single-celled microbe – an 'archaean' – engulfed another single-celled microbe – a bacterium. Instead of being consumed, the bacterium survived and multiplied in its host. The archaean and its bacteria provided each other with benefits they could not obtain alone.

At first, however, dying bacteria released 'jumping genes' that damaged their archaean's DNA. This was thwarted through the evolution of a membrane to surround and protect the host's genome. Therefore, 'eukaryotes', with a membrane-enclosed genome and other cell structures, evolved to tame their internal bacteria. Additionally, genetic damage by the bacteria's jumping genes triggered the evolution of sexual reproduction. Swapping genetic material with other archaeans allowed damaged parents to produce undamaged offspring.

Over time, these bacterial helpers and their hosts became ever more interdependent. Eventually the bacteria, unable to venture outside to another host, were passed only from hosts to their offspring. Now they had to help their hosts, because they reproduced only when their hosts did. In turn, their hosts could not live without these bacteria's efficient metabolism of energy-rich compounds, which enabled host cells to grow larger and evolve larger genomes.

The descendants of these helper bacteria are the mitochondria in our cells, now as much a part of us as our DNA. Having evolved mechanisms to incorporate and tame helper microbes, eukaryotes had less difficulty acquiring additional helpers that gave them new abilities, such as the photosynthetic bacteria that gave their hosts photosynthesis. Only eukaryotes, with their larger size and larger genomes, evolved complex multicellular organisms – plants, animals and fungi – because only they could evolve the complex coordination among cells needed to make complex, functional multicellular organisms.

Making multicellular organisms started with forming clumps of genetically identical cells, each descended from a single,



sexually produced, genetically unique ancestor. Because a clump's cells were genetically identical, a gene benefited as much from helping a neighbouring cell as its own. Leigh remarks that because the cells of each clump were genetically identical, whereas each clump was genetically unique, selection acted on whole clumps, not individual cells. 'In successful lineages, clumps evolved division of labour and means of coordination among their cells, entailing progressively more elaborate differentiation of cells into different tissues and organs,' he explains.

In animals with billions of cells, however, mutant cells may appear that 'cheat' by multiplying cancerously rather than doing their jobs for the animal. Animals have evolved defences such as specialised 'policing' cells that consume such cheater cells.

Building Animal Societies

Forming animal societies also poses problems of ensuring cooperation and preventing cheating. As with other systems, mechanisms to prevent or punish non-cooperation have evolved to thwart cheaters, nudging the system back towards stable cooperation.

For example, social honeybees solve the problem of reproductive competition by only having one reproductive female – the queen. The queen's daughters – the workers – are more closely related to the queen's eggs than their sisters' eggs. Workers therefore destroy the eggs of any other worker that tries to cheat by producing her own eggs rather than helping her queen reproduce.

Cooperation also occurs between members of different species. Mutualism can be essential for the survival of each cooperating species. Mutualism promotes increased complexity and diversity of ecosystems. Most mutualisms, however, require mechanisms that prevent 'cheating' – benefiting from the fruits of cooperation without contributing to them. 'Mutualism

among species is as essential to the productivity and species diversity of ecosystems as cooperative enterprise and trade are to the productivity and diversity of occupations of human economies,' Leigh explains.

For example, the spectacular coral reefs we see today exist thanks to an early mutualism between a coral and photosynthetic algae called zooxanthellae. The algae provided their host coral with photosynthesised sugars; the coral provided the algae with secure shelter and fertilising nutrients. Mutualism is normally enforced, not by baby corals inheriting live-in zooxanthellae from a parent, but by the ability of corals to expel non-performing algae and of algae to abandon non-performing corals. Coral-algal cooperation enabled these corals to become immensely productive and to produce large, diverse reefs sheltering many other forms of life.

Ecosystems as Commonwealths

Evolutionary progress involves a trend towards cooperation that enhances productivity, diversity and interdependence. By resisting deviations towards cheating and wastage, highly productive and diverse ecosystems endure for long periods.

Harmony in ecosystems, however, is never complete. Predators and herbivores will always be with us. Predators are essential regulators of ecosystems: for example, wolves protect the productivity and diversity of temperate-zone forests by keeping deer and boar from over-browsing, incidentally assuring these herbivores an enduring living. Even herbivory can acquire mutualistic aspects. The great grazers of east Africa protect grasslands by destroying tree saplings, which protects their future food supply by preventing forest from replacing the grassland.

However, because ecological communities are organised by natural selection over many millennia, any form of unprecedented major disturbance can abruptly diminish their productivity and diversity. Major extinctions punctuate the history of life on Earth. Diversity and productivity recover in a few million years after the crisis passes, exemplifying the normal tendency of Earth's ecosystems to increase in productivity and diversity. Ecosystems that arise from the surviving organisms, however, may differ greatly from those that existed before the disturbance.

One of the best-known mass extinctions occurred when an asteroid struck the earth approximately 66 million years ago, killing off the non-avian dinosaurs. Millions of years later, the recovered ecosystems were as – or more – productive and diverse as pre-extinction ecosystems. However, the dinosaurs that roamed the Earth are gone forever.

Human disturbance can also be disastrous. Thanks to interdependence among species, the impacts of unprecedented disturbance on ecosystems could be far greater than expected. For example, as Leigh explains: 'Eliminating sea otters allowed sea urchins to destroy productive kelp beds, replacing them by appropriately named urchin barrens which supported much lower diversity.' Here, an entire ecosystem was degraded by eliminating one species.

Although evolutionary history suggests that life will recover from humans' destructive activities, human beings might not be among the survivors. Past extinctions are stark warnings that the planet's interdependent ecosystems are fragile – and utterly irreplaceable.

Coda

How natural selection favours cooperation helps us understand how natural selection could favour the evolution of the beauty, diversity and overflow of life we see in nature. As Darwin remarked at the close of *The Origin of Species*, 'Thus, from the war of nature, from famine and death, the most exalted object we are capable of conceiving, namely the production of the higher animals, directly follows. There is grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has been cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved.'

Meet the researcher

Dr Egbert Giles Leigh, Jr
Independent Researcher
Baltimore, MD
USA

Dr Egbert Giles Leigh Jr was a Biologist at the Smithsonian Tropical Research Institute in Panama, where he resided for almost 50 years. He has since retired, and is now an independent researcher in Baltimore. After completing an undergraduate degree in Mathematics at Princeton University, Dr Leigh earned his PhD in Biology at Yale University. Beginning his academic career as an assistant professor at Princeton University, he was soon invited to join the Smithsonian Tropical Research Institute as a researcher. Dr Leigh's main research interests include evolutionary biology and community ecology; his work on tropical forest ecosystems is well-known and internationally celebrated. Over the course of his career, Dr Leigh has published around 200 research articles and several books, including 2019's *Nature Strange and Beautiful: How Living Beings Evolved and Made the Earth a Home*, which Yale University Press describes as 'A beautifully written exploration of how cooperation shaped life on earth, from its single-celled beginnings to complex human societies.'

PROFILE

W: https://stri.si.edu/story/profile-egbert-leigh

FURTHER READING

EG Leigh Jr, C Ziegler, Nature Strange and Beautiful: How Living Beings Evolved and Made the Earth a Home, Yale University Press, 2019.

EG Leigh Jr, Cooperation, Evolution of, In Reference Module in Life Sciences, Elsevier, 2017.
DOI: 10.1016/B978-0-12-809633-8.02340-2

JA Estes, Serendipity: An Ecologist's Quest to Understand Nature, University of California Press, 2016.

Nick Lane, The Vital Question: Energy, Evolution, and the Origins of Complex Life, WW Norton, 2015.

EG Leigh Jr, The evolution of mutualism, Journal of evolutionary biology, 2010, 23, 2507.
DOI: 10.1111/j.1420-9101.2010.02114.x

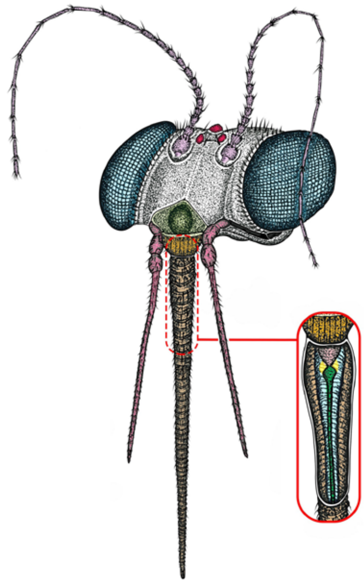
EG Leigh Jr, The group selection controversy, Journal of evolutionary biology, 2010, 23, 6.
DOI: 10.1111/j.1420-9101.2009.01876.x

EG Leigh Jr, Genes, bees and ecosystems: the evolution of a common interest among individuals, Trends in Ecology & Evolution, 1991, 6, 257.
DOI: 10.1016/0169-5347(91)90073-7

EG Leigh Jr, When does the good of the group override the advantage of the individual?, Proceedings of the National Academy of Sciences, 1983, 80, 2985.
DOI: 10.1073/pnas.80.10.2985

PREDICTING THE FUTURE OF INSECTS BY STUDYING THEIR PAST

Insects are one of the most important – and ancient – groups of organisms. They were around long before dinosaurs roamed the planet and before plants evolved flowers. Fossils from millions of years ago are a priceless record of ancient insects, helping scientists to piece together the evolutionary history of modern species. Insects contained in amber and sedimentary deposits can give us valuable clues about their life histories and ecology. Smithsonian National Museum of Natural History curator and researcher, **Dr Conrad Labandeira**, has been examining the insect fossil record to answer important questions with implications for today's living species.



A long-proboscid scorpionfly.

Studying Ancient Ecosystems

A time traveller taking a trip into deep history might be astonished by the alien world that greets them. Arriving 125 million years ago during the Early Cretaceous Period, our intrepid traveller sees a world dominated by giant conifers, ferns, and ancient cycad trees, with enormous dinosaurs roaming the landscape.

On closer inspection, some familiar features are revealed – a beetle munches away at a leaf while a tiny, spined mammal scurries through the undergrowth nearby. Fast-forward by about 30 million years – forever to us, but a mere fraction of our planet's history – would reveal a remarkably different world, filled with flowers, the earliest bees, mosquito-sized scorpionflies with long proboscises, and lizards.

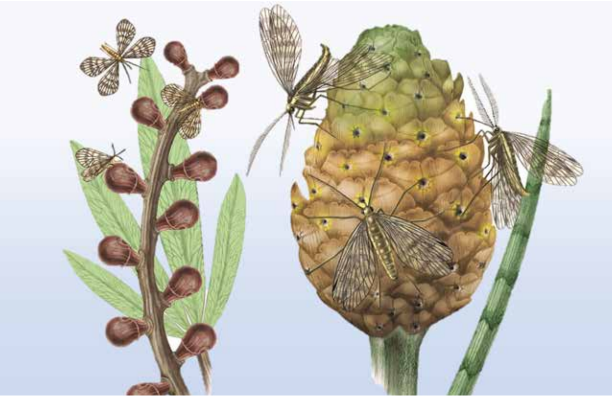
Unfortunately for bold modern scientists, studying the wildlife of the past must be done without the advantage of a time machine. Fortunately, many plants and animals left evidence of their existence for us to discover, millions of years later. Fossils are like natural time capsules, preserving a record of the distant past, and one of the crowning glories of the fossil world must be amber. Insects and other invertebrates, plants, lizards, and even dinosaur feathers have all been frozen in time in the sticky tree resin and solidified into the honey and orange-coloured lumps we see today. Amber fossils can be incredibly detailed, preserving minute details perfectly in 3D. In some cases, even the colours and delicate surface ornamentation of organisms have been preserved.

The general principles governing the evolution and ecological relationships of organisms are the same across history – whether 1 year ago or 100 million years ago. For example, natural selection drives organisms to adapt to their environment over generations or the lineage will perish. Scientists can apply these principles to fossil records to build a picture of ancient ecosystems. Dr Conrad Labandeira, a palaeobiologist from the Smithsonian National Museum of Natural History, has spent most of his esteemed career doing just that.

Dr Labandeira curates the museum's extensive insect fossil collection – over 140,000 specimens and counting – of extinct species of insects and their ancestors that lived between 410 million years ago to 11,700 years ago. However, he also travels to the far corners of the planet to find insects and their associated plants, in order to address a particular evolutionary or ecological question of the deep past.

For instance, if the question is, 'What happened to insects and their associations with plants at the end of the Permian Period?', Dr Labandeira travels to South Africa to study the Karoo deposits. If he wishes to investigate the development of pollination syndromes during the Jurassic and Cretaceous Periods, he travels to Northeastern China. 'And then there is the response of insect herbivores to the Palaeocene–Eocene Thermal Maximum, a brief time of dramatic global change 56 million years ago, for which my go-to place is Wyoming, in the US,' he says.

By applying his knowledge of taxonomy, anatomy, and ecology, he aims to understand how these species interacted with their environment, when specific adaptations evolved in insect lineages, and how insects responded to global changes. His work helps us predict how modern insect groups might respond to climate change, changes in land use, and other environmental pressures.



Left: scorpionflies on Caytonia cupules. Right: larger scorpionflies on Alvinia bohemica cone. CREDIT: Mary Parrish.

False blister beetle carrying pollen. CREDIT: José Antonio Peñas.

Immortalised Insects

Like other animals, insects need a particular set of conditions to become fossilised. Their hard, external skeleton means that this occurred more frequently than for soft-bodied animals, such as worms, but their small size decreased the likelihood of fossilisation. However, in some deposits, insects occur in heightened preservation, and abundance. 'As such, the insect fossil record is woefully incomplete overall, but is also driven by occasional and exceptional occurrences,' says Dr Labandeira. 'There is much still left to discover about their history.'

Amber-resin trees became more common during the Cretaceous Period, between 145 million years ago to 66 million years ago. Because amber forms from tree resin, the insects trapped in amber can reveal ancient plant-insect relationships. The evolution of insects and plants is intricately linked throughout their history, and some of the most interesting – and important – ecological events occurred during the Cretaceous Period.

In the early part of this period, from about 125 million years ago to 90 million years ago, 'gymnosperms' (cone-bearing plants) were replaced by 'angiosperms' (flowering plants) as the dominant vegetation on Earth. This switch – called the 'Cretaceous Terrestrial Revolution' – had profound effects on insect pollinators and herbivores. 'The patterns of extinction, origination and continuity of insect pollinators and herbivores across this 35-million-year-long interval provide a global perspective of how insects evolutionarily and ecologically contend with a changing world,' explains Dr Labandeira.

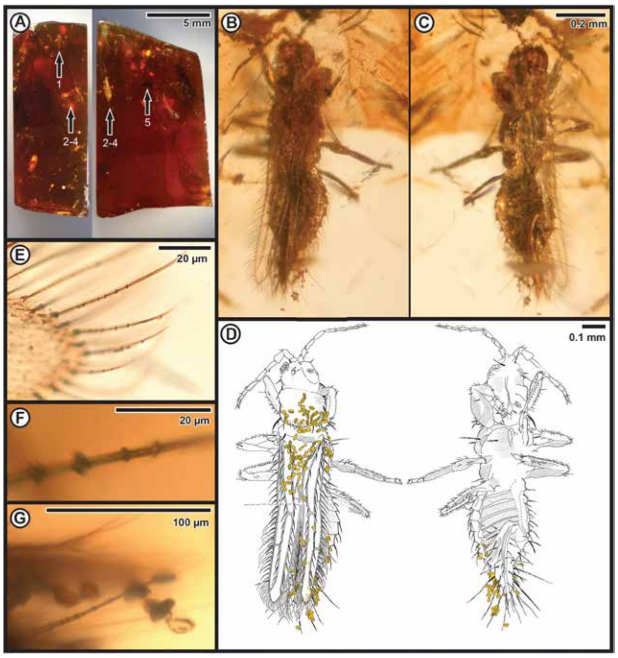
Ancient Pollinators

Dr Labandeira's work helped answer an age-old chicken and egg question: did insect pollination or flowers come first? 'The idea that insect pollination may have preceded the angiosperms was substantively hypothesised during the 1970s, although it was disputed,' he says. Through extensive research, his team identified four pollination modes existing before the Cretaceous Terrestrial Revolution, based on the feeding method and mouthparts of the insect groups and the features and structures of the plants. These are fly sponging, beetle chewing, thrips punch-and-suck feeding, and siphoning through a long straw-like mouthpart element called a proboscis.

Alongside David Peris and other colleagues from Spain, Dr Labandeira examined a false blister beetle trapped in Spanish amber along with 126 pollen grains from a gymnosperm, likely a cycad species. This provides compelling evidence that this beetle's chewing behaviour facilitated the pollination of gymnosperms before the Cretaceous Terrestrial Revolution, at which point this beetle family transitioned to angiosperm feeding. 'This was a very rare discovery – to find a group of closely related beetles where some species are associated with gymnosperm pollen, and others are associated with angiosperm pollen in the same amber deposit,' says Dr Labandeira.

Similarly, the researchers examined four thrips specimens covered with cycad pollen and trapped in Spanish amber. Dr Labandeira suggests that the hair-like rings flanking the wings and abdomen of these insects represent a specialised structure for carrying pollen grains, much like the branched hairs on the mouthparts and legs of modern bees.

Dr Labandeira and his colleagues and students discovered a fifth lineage of insects with long proboscises in Myanmar amber. Their studies involved anatomical examination of several specimens, including making a careful cross-section of one specimen to reveal the internal structures of the insect's mouthparts. The scorpionfly genus, which they named *Dualula*, had a specialised pump system that helped it extract nectar-rich 'pollination drops' from the reproductive organs of gymnosperms. It lived alongside nectar-feeding moths, beetles, and flies, providing evidence that during the Cretaceous Terrestrial Revolution, there was an overlap in time when insects were simultaneously feeding on gymnosperm pollination drops and angiosperm nectar. Long proboscises evolved separately on at least 13 occasions throughout the history of mid-Mesozoic insects.



(A) Amber containing six specimens of the thrips genus Gymnopollisthrips. (B) Thrips with attached pollen grains. (C) Underside of the same specimen. (D) Drawings based on B and C, with pollen grains indicated in orange. (E) Hair-like rings (setae), and (F) magnification. (G) Ring setae showing the adherence of 12 clumped pollen grains. From Proceedings of the National Academy of Sciences, 2012, 109, 8623 doi.org/10.1073/pnas.1120499109.

Finally, alongside colleagues from Russia and the Czech Republic, Dr Labandeira discovered an ancient fly from the early Cretaceous Period, which exhibited the sponging mouthparts and feeding behaviour we see in today's species, such as common houseflies. The specimen they examined had pollen stuck to its face, near its mouthparts, in a pattern often seen in modern pollinating fly species.

The evidence points to specialised insect pollination evolving at some point during the Permian Period between 300 million years ago to 250 million years ago – at least 140 million years before the first flowering plants appeared. 'Such early interactions most likely acted as an evolutionary and ecological prelude to later interactions between early angiosperms and their insect pollinators during the Cretaceous,' explains Dr Labandeira.

Predicting Modern Responses from Ancient Evidence

The transition from a gymnosperm to angiosperm-dominated world had an immense effect on the resources and habitats available to insects. During the Cretaceous Terrestrial Revolution, four major evolutionary patterns occurred in pollinating insect lineages. 'All four examples involve pollinating insects with very different mouthparts,' says Dr Labandeira.

Some insect lineages, such as the false blister beetles, transitioned from their gymnosperm hosts to angiosperm hosts. Others, failing to adapt to their changing world, such as some ancient fly lineages, simply went extinct. Some, such as specialised thrips, persisted on their gymnosperm hosts but were greatly reduced in diversity. Finally, new insect lineages with angiosperm associations originated during this interval, such as bees.

Insects that transitioned to angiosperm hosts and those that originated with angiosperm associations flourished. Today, 85% of angiosperms are animal-pollinated, overwhelmingly by insects. Insect pollination, in turn, drove angiosperm lineages to become incredibly diverse as plants adapted and new species arose with ever-closer associations with their insect pollinators. These co-associations occasionally became co-evolved, meaning that many of today's insects and plants are intricately linked, such as figs and fig wasps.

However, despite fluctuations in genus and species-level diversity, insect family-level diversity from 201 million years ago to 23 million years ago remained relatively stable, puzzling scientists for years. To resolve this mystery, Dr Labandeira conducted a detailed investigation of 280 plant-associated insect families from throughout this period and developed a method to control for the effects of gaps in the fossil record. Along with his other findings, this work provides evidence that the loss of some families and origination of new ones has given the appearance of family-level diversity stability.

For example, 95 plant-associated insect families are documented just before the Cretaceous Terrestrial Revolution, and 110 after the angiosperm explosion. Dr Labandeira demonstrated that family-level diversity of plant-associated insects plummets – an event called the 'Aptian-Albian gap' – and then rises again after a lag period in which insect adaptation occurs. Without examining these fine-scale changes the real patterns of diversity can be masked over sufficiently large timescales, with consequences for our understanding of today's insect groups.

'The history of insect diversity in deep time, which has the potential to demonstrate the impact of mass extinction, has taken on particular urgency in light of the escalating concern over a potential mass extinction of insects during the twenty-first century,' explains Dr Labandeira. In particular, the research of Dr Labandeira and his colleague Sandra Schachat of Stanford University in California could aid predictions for how global events, such as rising atmospheric carbon, climate change, and loss of habitats might impact different insect groups based on their ecology and evolutionary history.

Dr Labandeira and his colleagues' investigations into the gymnosperm-angiosperm transition during the Cretaceous Terrestrial Revolution previously focused on insect pollinators. To complete our understanding of this significant event, Dr Labandeira is mentoring doctoral student Lifang Xiao, and colleagues from Capital Normal University, who are currently investigating the Cretaceous Terrestrial Revolution from the perspective of insect herbivory patterns.

Meet the researcher

Dr Conrad C. Labandeira
Department of Paleobiology
National Museum of Natural History
Smithsonian Institution
Washington, DC
USA

Dr Conrad C. Labandeira graduated with a PhD with an emphasis in Palaeobiology from the University of Chicago, after which he continued his research in a postdoctoral position in Plant Biology and Entomology at the University of Illinois at Urbana-Champaign. He has spent the majority of his esteemed career at the Smithsonian National Museum of Natural History, where he currently holds the positions of Senior Research Scientist and Curator of Fossil Arthropods. His main research interests include fossil insect-plant associations including herbivory, pollination, mimicry, and plant defences, insect evolutionary convergence and diversity, and past terrestrial food webs. Dr Labandeira has co-supervised over 36 projects by senior undergraduate, masters, doctoral, and postdoctoral researchers. He has been awarded numerous honours for research excellence and has been elected to Fellow for both the Geological Society of America and the Paleontological Society.

CONTACT

E: labandec@si.edu
W: https://naturalhistory.si.edu/staff/conrad-labandeira

KEY COLLABORATORS

Dr Mónica Carvalho, Smithsonian Tropical Research Institute, Panamá
Dr Ellen Currano, University of Wyoming, USA
Dr David Dilcher, Indiana University, USA
Dr Michael Donovan, Cleveland Museum of Natural History, USA
Dr Enrique Peñalver, Instituto Geológico y Minero de España, Spain
David Peris, University of Bonn, Germany
Sandra Schachat, Stanford University, USA
Anshuman Swain, University of Maryland, and NMNH, Smithsonian Institution, USA
Dr Yongjie Wang, Dr Xiaodan Lin, and Lifang Xiao, Capital Normal University, China
Dr Torsten Wappler, Hessisches Landesmuseum Darmstadt, Germany
Dr Peter Wilf, Pennsylvania State University, USA
Dr Bo Wang, Nanjing Institute of Geology and Palaeontology, Nanjing, China

FUNDING

Smithsonian Institution
National Science Foundation
Deutsche Forschungsgemeinschaft

FURTHER READING

X Lin, CC Labandeira, C Shih, CL Hotton, D Ren, Life habits and evolutionary biology of new two-winged long-proboscid scorpionflies from mid-Cretaceous Myanmar amber, Nature Communications, 2019, 10, 1235. doi.org/10.1038/s41467-019-09236-4

SR Schachat, CC Labandeira, ME Clapham, JL Payne, A Cretaceous peak in family-level insect diversity estimated with mark–recapture methodology, Proceedings of the Royal Society B, 2019, 286, 20192054. doi.org/10.1098/rspb.2019.2054

D Peris, R Pérez-de la Fuente, E Peñalver, X Delclòs, E Barrón, CC Labandeira, False blister beetles and the expansion of gymnosperm-insect pollination modes before angiosperm dominance, Current Biology, 2017, 27, 897. doi.org/10.1016/j.cub.2017.02.009

E Peñalver, CC Labandeira, E Barrón, X Delclòs, P Nel, A Nel, P Tafforeau, C Soriano, Thrips pollination of Mesozoic gymnosperms, Proceedings of the National Academy of Sciences, 2012, 109, 8623. doi.org/10.1073/pnas.1120499109

D Ren, CC Labandeira, JA Santiago-Blay, A Rasnitsyn, C Shih, A Bashkuev, MA Logan, CL Hotton, D Dilcher, A probable pollination mode before angiosperms: Eurasian, long-proboscid scorpionflies, Science, 2009, 326, 840. doi.org/10.1126/science.1178338

NATIONAL MUSEUM of NATURAL HISTORY
Smithsonian

NATIVES PROGRAM TRAINS NATIVE AMERICANS IN ENTOMOLOGY

Insects are the most diverse lifeform on Earth. However, entomology, the scientific study of insects, is a field with few graduates. To address rising issues in agricultural biosecurity, pest management and biodiversity preservation, we need more trained entomologists. Moreover, because insects impact the health and well-being of almost everyone, there is also a need to increase diversity and to train underrepresented groups in entomology. One such group is Native Americans. To address the lack of entomologists in this key demographic, **Dr W. Wyatt Hoback** and a team from Oklahoma State University pioneered a program to engage Native American undergraduate students in entomology.

The Need for Native American Entomologists

The US is home to 574 recognised, sovereign tribal nations. These nations are responsible for managing their lands and for the health and wellbeing of their citizens. In most cases, tribal nations have expressed a strong desire for self-efficacy in government, with the hope that tribal citizens obtain leadership positions, particularly within the sciences.

Despite this, Native Americans are severely underrepresented within science, technology, education, and mathematics (STEM) fields. Dr Wyatt Hoback recognised this problem at his own institution, Oklahoma State University (OSU), where Native American students represent only 6% of enrolment in the Division of Agriculture and Natural Resources, despite making up over 13% of the Oklahoma population.

In 2016, only two of 43 entomology undergraduates were Native Americans. This dearth of Native American entomology students translates to a lack of trained entomologists to manage pest insects and conserve beneficial insects on Native American lands. This is of particular concern in Oklahoma, where 39 federally recognised tribes manage nearly half of the state's land.

The lack of Native American entomologists may explain worrying trends, such as the fact that Native American communities in Oklahoma are two to four times more likely to be infected with tick-borne diseases when compared with the population at large. Additionally, the mosquito vectors of Zika, Dengue and Chikungunya viruses have been found in Native American lands in Oklahoma. Furthermore, cattle production, a lucrative economic endeavour by most Native American nations in parts of Oklahoma, has suffered from a lack of effective pest control and conservation practices.

Thus, training Native American students in entomology in Oklahoma is an immediate need that will have direct benefits for the students, Native American communities, and the state. At a larger scale, the field of entomology is under threat. With declined interest

in the field since the 1990s, there is a great need for experts to address issues in pest management, as well as to work towards the conservation of insects, which are essential to the functioning of almost all terrestrial ecosystems on Earth. Indeed, with biodiversity plummeting across the globe, particularly amongst insects, there has never been a more urgent time to recruit entomologists.

To promote entomology amongst Native American students, Dr Hoback and his colleagues at OSU and OSU's Center for Sovereign Nations, designed and developed a program aimed at engaging Native Americans in agricultural sciences. The 'Native Americans Trained in Various Applied Entomological Sciences', or 'NATIVES', program received funding in 2016 from the US Department of Agriculture (USDA). With five graduated students as of 2021, the program and has shown promising success in engaging Native American students with entomology, empowering them to tackle emerging challenges in their communities.

Global Entomology Problems Require Local Experts

The US is vulnerable to agricultural threats, particularly from insects that transmit diseases to human and animals. For example, outbreaks of West-Nile virus in livestock, a disease transmitted by mosquitos, resulted in serious animal welfare concerns and the loss of billions of dollars.

Of course, insects also threaten human health. For example, Lyme disease and Rocky Mountain Spotted Fever, both transmitted by ticks, are predicted to become more prevalent as global climate change lengthens the season in which ticks are active. Unfortunately, this trend is also expected for mosquito-borne diseases such as West Nile and Zika viruses. Unfortunately, the US, due to a lack of trained experts, is underprepared to manage these threats and other potential crises, such as the emergence of new insect-transmitted diseases.

A lack of recruitment of new and diverse entomologists has the potential to have severe and devastating consequences. Trained experts also must be able to collaborate and communicate across jurisdictional and cultural boundaries. This is especially true in areas that are largely managed by Native American governments, such as Oklahoma. 'The lack of trained entomologists from diverse backgrounds exacerbates losses caused by insects because of difficulties with communication that arise from racial, cultural, and ethnic diversity,' explains Dr Hoback. The NATIVES program is the first of its kind in the US, immersing a group of undergraduate students from diverse Native American nations into entomology and agricultural biosecurity studies.

An Emphasis on Mentorship and Service

In 2017, five Native American (Choctaw and Cherokee) students were recruited to the Entomology undergraduate major at OSU. To support these students, scholarships and training opportunities were made available every year.

'Each class I took during my freshman and sophomore years was very interesting, and I began to realise that insects had a connection with almost everything in our ecosystem, which is very fascinating to me,' said Bailee Posey, one of the students in the program.

In designing NATIVES, Dr Hoback and his colleagues prioritised the role of mentorship. Using the 'cohort model' approach, which places all the students in the same discussion-heavy courses, camaraderie was quickly built.

Additionally, Dr Hoback and his colleague acted as academic and cultural advisors to the students. While Dr Hoback served as the principal academic advisor for all students, Elizabeth Payne, Director of the Center for Sovereign Nations, helped the students to integrate into university life.

'On top of the classes, all of my entomology professors have been great teachers and mentors,' adds Bailee. 'Particularly, I think of the two women in the department that have inspired me as an entomologist and who I want to be as a woman in science.'

Since a large focus of the NATIVES program is allowing students to give back to their communities, there is also an emphasis on outreach and education. Students were required to complete Internships in Teaching and Outreach, which allowed students to develop teaching strategies and gave them the chance to conduct entomological outreach.

For example, as part of OSU's 'Insect Adventure', the first group of NATIVES students gave entomological presentations and demonstrations to K-12 students within their own communities. Additionally, the students collaborated to lead a three-day 'Bug Camp' for 30 youth of the Choctaw Nation. The students also attended the Southwest branch meeting of the Entomological Society of America in Tulsa, where they helped develop stations for the 'Insect Expo', introducing primary school children to the roles that insects play in food production and human health.

'The Insect Expo was a good time for me,' said TK Wallace, one of the students in the program. 'For one, I enjoy being around kids. Some kids don't get the opportunity to learn about science and get the time to do it in a fun environment. So just knowing I could make a kid's day better brings me a little bit of joy. Additionally, it was a really good networking opportunity. I had a lot of professionals in the field come up to me and complement me on my project.'

Such activities gave NATIVES students invaluable outreach experiences, while also serving to inspire children to become interested in the field of entomology.

Networking in Research and Industry

As a requirement of the Entomology program, NATIVES students conducted independent research projects. The research topics were diverse, related to a variety of entomological topics such as food safety, disease pathogens, forensic entomology, and insect biodiversity. For example, one NATIVES student, Taylor Coles, analysed insect biodiversity in Oklahoma and presented her data at the annual National Entomological Society of America meeting. Another student, Alexis Coles, analysed the pathogens present in various tick species found in Oklahoma.

'I loved all of my research projects because they all gave me more insight to what research really is,' she said. 'I also learned that there is still so much that needs to be tested and nothing is ever proven, just supported. Dr Wayadande was not only my research supervisor but is a mentor that I look up to and strive to achieve her positive attitude.'

The independent research projects introduced students to the entire research process, from developing a question and hypothesis to analysing data and presenting results. Consistent with the cooperative focus of NATIVES, the students engaged with each other's research, providing valuable collaborative and professional experience. Along with presentations at relevant conferences, students had the opportunity to regularly meet with USDA representatives, Oklahoma-based conservation groups, and tribal nation leadership.

As well as developing sound research skills, the NATIVES program gives students the chance to interact with potential future employers. Students are regularly taken to visit facilities within OSU, such as the Agricultural Products Center and the School of Veterinary Medicine, and to external sites, such as livestock farms, within the state.

The Future of NATIVES

As of 2021, five NATIVES students have graduated from the program. Thanks to the specialised curricula, mentorship, and unique research and outreach opportunities, these Native American graduates are highly trained, scientifically competent entomologists who are well-positioned to further their careers.

Two of the students are pursuing graduate degrees in entomology, and the others are working in government or hospital positions. Given the success of the program's first iteration, additional funding was secured to continue and grow the NATIVES program. Additionally, though the program was designed to provide training to Native Americans, it spurred renewed interest in the field, and improved the core curriculum and experiences of all students in the OSU entomology undergraduate degree program.

With more programs like NATIVES, designed to meet a specific regional need, urgent national and global issues can be addressed.

Meet the researcher

Dr William Wyatt Hoback
Department of Entomology and Plant Pathology
Oklahoma State University
Stillwater, OK
USA

Dr W. Wyatt Hoback is a passionate entomologist, who has focused on excellence in teaching and mentorship throughout his career. Since receiving his PhD in Entomology from the University of Nebraska in 1999, Dr Hoback has dedicated his career to increasing the number of students earning entomology degrees. In 2014, he accepted his current position with the Department of Entomology and Plant Pathology at Oklahoma State University (OSU), where he teaches more than 600 students each year and has mentored over 60 graduate students. He is also active in research, and has published more than 130 peer-reviewed research articles and 15 articles related to teaching. At OSU, he has worked tirelessly to spark interest in entomology, helping grow the major from twelve to nearly 80 students. In 2017, he received the Entomological Society of America's Distinguished Teaching Award and in 2020, he was recognised with the National Excellence in Teaching and Student Engagement award from the US Department of Agriculture. Dr Hoback is the lead investigator for the successful 'Native Americans Trained in Various Entomological Sciences (NATIVES)' program, which engages underrepresented Native American students in entomology.

CONTACT

E: whobak@okstate.edu
W: https://experts.okstate.edu/whoback

KEY COLLABORATORS

Elizabeth Payne, JD. Director of the Center for Sovereign Nations
Dr Bruce Norden, Medical and Veterinary Entomologist, Oklahoma State University
Dr Justin Talley, Livestock Extension Entomologist, Oklahoma State University
Dr Astri Wayadande, Vector Entomologist, Assistant Director of National Institute for Microbial Forensics & Food and Agricultural Biosecurity (NIMFABB)

FUNDING

The Division of Institutional Diversity, Oklahoma State University
United States Department of Agriculture Multicultural Scholars Program

FURTHER READING

B Theis, Road Less Travelled: Native American freshmen choose an entomology adventure, STATE Magazine, 2017, 68–67.

AM Folkema, RC Holman, FS Dahlgren, JE Cheek, JH McQuiston, Epidemiology of Ehrlichiosis and Anaplasmosis among American Indians in the United States, 2000-2007, The American Journal of Tropical Medicine And Hygiene, 2012, 87, 529–537.

SHINING NEW LIGHT ON THE COMPLEX WORLD OF FUNGI

From microscopic, single-celled yeasts to a mycelium that can cover many acres underground, fungi represent a diverse array of organisms. However, despite their global distribution, diverse growth forms, and complex interactions with other organisms, we still know very little about fungi. This lack of knowledge is reflected in the numbers: although it is estimated that there are between 1.5 and 6 million species of fungi, only around 138,000 have been described. **Dr Danny Haelewaters** of Ghent University is contributing to closing the gap in our understanding. His team's research explores the diversity of fungi, in addition to their evolutionary history and ecological interactions with other groups of organisms.

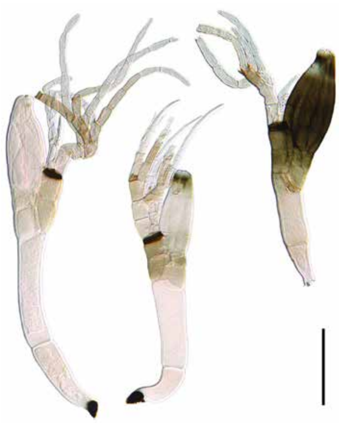
An Understudied Kingdom

Although most people immediately recognise mushrooms, with their well-known cap and stem, many other fungi, such as yeasts and moulds, are microscopic. Despite their importance, many of these fungi have been overlooked, with millions of species still awaiting description.

'Fungi are essential to ecosystem functioning, they occur virtually everywhere and form complex mutualisms with diverse organisms including prokaryotes, algae, plants, invertebrates, vertebrates, and other fungi,' says Dr Danny Haelewaters, a researcher at Ghent University in Belgium, who studies the classification, biology, and ecology of fungi.

Dr Haelewaters has contributed substantially to known fungal diversity, describing and documenting more than fifty new species. One microscopic fungus, discovered and described by Dr Haelewaters, is *Laboulbenia quarantenae*, which he named after the lockdown measures that were in place at the time due to the global COVID-19 pandemic. Although the pandemic caused much of Dr Haelewaters' field studies to be cancelled, it serendipitously gave him and his colleague the time they needed to finally describe the species.

Describing new fungi such as *Laboulbenia quarantenae* is of interest to not only mycologists, but for anyone interested in ecological conservation and maintaining biodiversity. Some fungi, for example, are critical to the health and survival of plants. Others provide essential ecosystem services, such as the decomposition of matter into available nutrients for plants and animals. However, we cannot truly understand the role of fungi – or which fungal species are threatened – unless we first document their existence, understand their evolution, and study their basic biology. Armed with this knowledge, conservationists would be able to devise more effective strategies for protecting important fungal species, and their wider ecosystems.



Thalli of Laboulbenia quarantenae, named after the COVID-19 quarantine period. Scale bar = 0.1 mm. Photo: André De Kesel.

Therefore, Dr Haelewaters has dedicated much of his career to researching two understudied classes of fungi: Laboulbeniomycetes and Leotiomycetes.

The class Laboulbeniomycetes is a unique group of fungi that form obligate relationships with insects and other arthropods. However, due to their microscopic size, peculiar

Ladybird infected by a species of Laboulbeniales. Photo: Bart Horvers.

morphologies, complicated life history, and the inability of many species to be grown in culture, they have been mostly neglected by mycologists. While Laboulbeniomycetes present a variety of challenges that preclude research, descriptions of species within the class Leotiomycetes have been comparatively extensive. However, attention has been mainly focused on species in the Northern Hemisphere, whereas the tropics, Africa, and Asia have been virtually unsampled.

In addition to describing new fungal species, Dr Haelewaters has also creatively used and in some cases developed new tools and technologies. When combined with traditional classification methods, his techniques have elucidated complex evolutionary relationships among species in these two classes of fungi. His current work has now branched into the ecological implications of the associations that fungi make with other types of organisms – leading to a whole new area of community ecology research, in which he asks questions about how climate and habitat may affect these associations.

Evolution of Parasitic Fungi

Of all fungi, parasitic fungi are perhaps the most understudied. The most diversified group of fungi within the Laboulbeniomycetes class is Laboulbeniales. This is an order consisting of fungi that live as external parasites on arthropod hosts. As 'obligate parasites', they must associate with a host in order to survive and reproduce. Colloquially known as 'beetle hangers', these tiny fungi appear to 'hang' from many arthropod species – mostly beetles – by attaching to their bodies. With 2,325 known species and many more awaiting descriptions, the Laboulbeniales order is quite species-rich.

Laboulbeniales can parasitise a wide range of arthropod hosts, including beetles, mites, millipedes, cockroaches, earwigs, and flies. Despite this broad host diversity, most of these fungi exhibit strict host specificity, with each species of fungi associating with only one species of host. However, some Laboulbeniales species are habitat-specific rather than host-specific, having multiple hosts that are in unrelated groups yet occur in the same habitat, such as underground caves or ant nests.

The unusual morphologies and microscopic size of Laboulbeniales species makes them difficult to study. This difficulty is compounded by the fact that, contrary to most fungi, researchers have not been able to grow Laboulbeniales in culture. Consequently, the relationships between Laboulbeniales and other members of its class, Laboulbeniomycetes, are still not well understood.

While previous research has mainly characterised Laboulbeniomycetes by grouping species based on their physical attributes, Dr Haelewaters was among the first to combine morphological methods with modern genetic sequencing and molecular tools, as well as ecological information, to evaluate their evolutionary history. Using this method on a parasitic fungus of ladybirds, he found that each ladybird species has its own unique species of fungus. This approach has also led to other fascinating discoveries. For example, Dr Haelewaters developed the first evolutionary tree of Laboulbeniomycetes based on multiple molecular markers, which describes how species in this group are related to one another and how they diversified. During this work, Dr Haelewaters established a new order, the Herpomycetales, to accommodate species that are exclusively associated with cockroaches.

Though Dr Haelewaters' contributions have been significant, he is dedicated to deepening our understanding of the evolutionary history of Laboulbeniomycetes further. 'Resolving evolutionary relationships among Laboulbeniomycetes is a long-term pursuit that I will continue to develop,' he says. To do so, he received funding to sequence an additional 25 fungal genomes.

Alongside their use of technological tools, Dr Haelewaters and his colleagues also connect concepts from theoretical ecology and fungal morphology, to make predictions on how morphology and distribution might influence host specificity. For example, some Laboulbeniales species penetrate the host tissue using a structure known as a haustorium, while others simply attach to the surface of their host's body. Dr Haelewaters hypothesises that, as hosts develop defence mechanisms, these fungal parasites with a haustorium adapt accordingly, which can lead to the evolution of new species. In other words, species with a haustorium are highly host-specific.

Gloeandromyces, which Dr Haelewaters discovered on a bat fly in Panama. Scale bar = 0.1 mm.

Parasites of Parasites

As obligate parasites, our understanding of the Laboulbeniales is only as good as our understanding of their host relationships. Since 2015, Dr Haelewaters has investigated the species-level diversity of Laboulbeniales associated with flies that parasitise bats. Between 2015 and 2020, Dr Haelewaters conducted field studies in Honduras and Panama, which resulted in the discovery of six new species of fungi being described and thousands more bat flies being added to a large repository of over 12,000 bat fly samples. His activities in Panama have led to a long-term collaboration with researchers at the Universidad Autónoma de Chiriquí to mentor students and investigate the local Laboulbeniales diversity.

This tripartite relationship between bats, bat flies, and parasitic Laboulbeniales fungi is globally common. Collaborating with Operation Wallacea and Taxon Expeditions, two networks of academics who implement biodiversity research expeditions with students and citizen scientists, Dr Haelewaters and his team are starting to monitor bats for the presence of bat flies in field sites in Central and South America, Europe, Africa, and Asia.

Dr Haelewaters and his colleagues plan to keep building on their repository to see if there are certain traits that are correlated with parasitism. For example, the researchers have already reported data indicating that local temperature and humidity influence parasitic prevalence of Laboulbeniales on their hosts. With human-induced habitat fragmentation altering ecosystems worldwide, it may be speculated that parasitism by Laboulbeniales could become more widespread in the future. The team hopes to continue to sample bats and bat flies to have a more robust repository of data, so that they can better understand the possible impacts of climate change and habitat fragmentation on Laboulbeniales fungi and their hosts.

Describing New Fungi

One of the largest questions in mycology is: What are the millions of fungi that have not yet been described, and where are they found? The Leotiomycetes class, understudied in Asia, Africa, and the tropics provides an excellent opportunity to examine both questions.

Dr Haelewaters is now part of an international team leading research into this class and is pioneering efforts to sample for species in previously unvisited areas. For example, Dr Haelewaters and his team received an EU INTERACT Transnational Access grant to sample peat bogs in Siberia, and funding from the United States National Science Foundation to support research in Mozambique, Ireland, and Central America.

Additionally, Dr Haelewaters started a long-term fungal survey at Cusuco National Park in Honduras in 2019 and has thus far collected over a hundred specimens, of which eleven likely represent undescribed species. Such a long-term study has the potential to greatly expand our understanding of fungal diversity, and – again – to evaluate the long-term effects of habitat disturbance due to climate change and activities such as deforestation.

Broader Implications

Understanding what type of species exist and where they are found is integral to creating and implementing conservation goals. Beginning to classify the millions of undescribed fungal species and their interactions with other organisms will expand our understanding of fungal diversity and their ecological roles.

Dr Haelewaters has contributed not only to sampling for these species, but in prioritising understudied areas and using modern-day tools and technologies that allow for fungal diversity to be placed in an evolutionary context. By expanding our knowledge of fungal species, including their evolution and complex ecological roles, conservationists will be far better equipped to protect Earth's precious biodiversity for future generations.

Meet the researcher

Dr Danny Haelewaters
Department of Biology
Ghent University
Ghent
Belgium

Dr Danny Haelewaters started off his career with an interest in animal science, and achieved a Bachelor's degree in Veterinary Medicine from the University of Antwerp in 2004. After the realisation that he did not want to work in a hospital setting, he discovered mycology, the study of fungi, and achieved a BSc and MSc in Biology at Ghent University. This was followed by a PhD in Organismic and Evolutionary Biology at Harvard University. He spent two years at Purdue University, where he was employed as a postdoctoral research assistant on a project to characterise the fungal microbial community of romaine lettuce. Dr Haelewaters is currently back at his alma mater, Ghent University, as a junior postdoctoral fellow. He is also currently a researcher at the University of South Bohemia and the Biology Centre of the Czech Academy of Sciences, both in České Budějovice, and holds an associate researcher position at the Universidad Autónoma de Chiriquí in Panama. Given his interdisciplinary background, it is no surprise that Dr Haelewaters has diverse research interests. Much of his work involves clarifying the evolutionary relationships of Laboulbeniales, an order of fungi that parasitise insects and other arthropods. However, he is also fascinated by the ecological implications of the interactions that these fungi have with their hosts. Finally, Dr Haelewaters is passionate about expanding our knowledge of fungal diversity and has pioneered fungal surveys in understudied habitats. Along with his research interests, Dr Haelewaters is enthusiastic about science communication and mentoring the next generation of scientists.

CONTACT

E: danny.haelewaters@gmail.com
W: www.dannyhaelewaters.com

KEY COLLABORATORS

M. Catherine Aime, Purdue University
André De Kesel, Meise Botanic Garden
Carl W. Dick, Western Kentucky University
Thomas Hiller, University of Hohenheim
Thomas E. Martin, Operation Wallacea
Oldřich Nedvěd, University of South Bohemia
Rachel A. Page, Smithsonian Tropical Research Institute
C. Alisha Quandt, University of Colorado, Boulder
Rosa V. Villarreal Saucedo, Universidad Autónoma de Chiriquí

FUNDING

Research Foundation – Flanders, Belgium
National Science Foundation, USA
David Rockefeller Center for Latin American Studies at Harvard University, USA
The Linnean Society of London
The Systematics Association, UK
University of South Bohemia, Czech Republic

FURTHER READING

M Perreau, D Haelewaters, P Tafforeau, A parasitic coevolution since the Miocene revealed by phase-contrast synchrotron X-ray microtomography and the study of natural history collections, Scientific Reports, 2021, 11, 2672.

D Haelewaters, M Blackwell, DH Pfister, Laboulbeniomycetes: Intimate fungal associates of arthropods, Annual Review of Entomology, 2021, 66, 257–276.

D Haelewaters, CW Dick, KP Cocherán Pittí, K Dittmar, BD Patterson, Bats, Bat Flies, and Fungi: Exploring Uncharted Waters, In: Lim B.K. et al. (eds) 50 Years of Bat Research, Fascinating Life Sciences, Springer, Cham, 2021, 349–371.

D Haelewaters, N Schoutteten, P Medina-van Berkum, TE Martin, A Verbeken, MC Aime, Pioneering a fungal inventory at Cusuco National Park, Honduras, Journal of Mesoamerican Biology, 2021, 1, 111–131.

SC Gonçalves, D Haelewaters, G Furci, GM Mueller GM, Include all fungi in biodiversity goals, Science, 2021, 373, 403.

Illustration by Valentina Ferro, showing Dr Haelewaters as "a real-life Indiana Jones that studies forgotten fungi instead of lost archaeological treasures".

EXPLORING MICROMETEOROLOGY IN PLANT STEMS AND FLOWERS

As complex living organisms, plants can often display intricate interactions with the air inside and around them. So far, however, many characteristics of these processes have gone largely unexplored. In their research, **Charlotte Coates** and **Dr Peter Kevan** at the University of Guelph combine field surveys with advanced imaging technologies to study the 'micrometeorology' that takes place in and around the stems and flowers of many plants. Their discoveries are shedding new light on how these plants grow and reproduce, and how some species are providing ideal habitats for ecologically damaging insects.

Micrometeorology

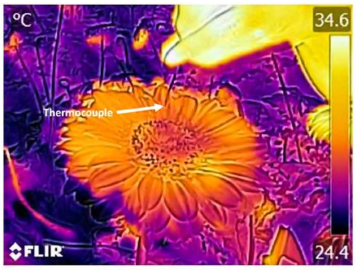
When we think about meteorology, we typically envisage weather patterns spanning vast regions of Earth's atmosphere: governed by factors including air temperatures, pressures, and moisture. However, these same effects are also highly relevant on far smaller scales, and can be studied through the field of 'micrometeorology'. Although the impacts of individual processes are minuscule compared with those in conventional meteorology, their combined effects can be crucial in understanding larger-scale processes.

One branch of micrometeorology considers the interaction between air and plants, with features including flowers, leaves, and stems. Because of their intricate, often complex living structures, heat can accumulate within and surround them in a unique variety of ways, introducing complex patterns in the flow of heat. Understanding these behaviours is key to studying how plants grow, feed, reproduce, and respond to changes in their surrounding environments – among a variety of other factors. Until recently, however, this level of knowledge remained sparse.

A Gap in Knowledge

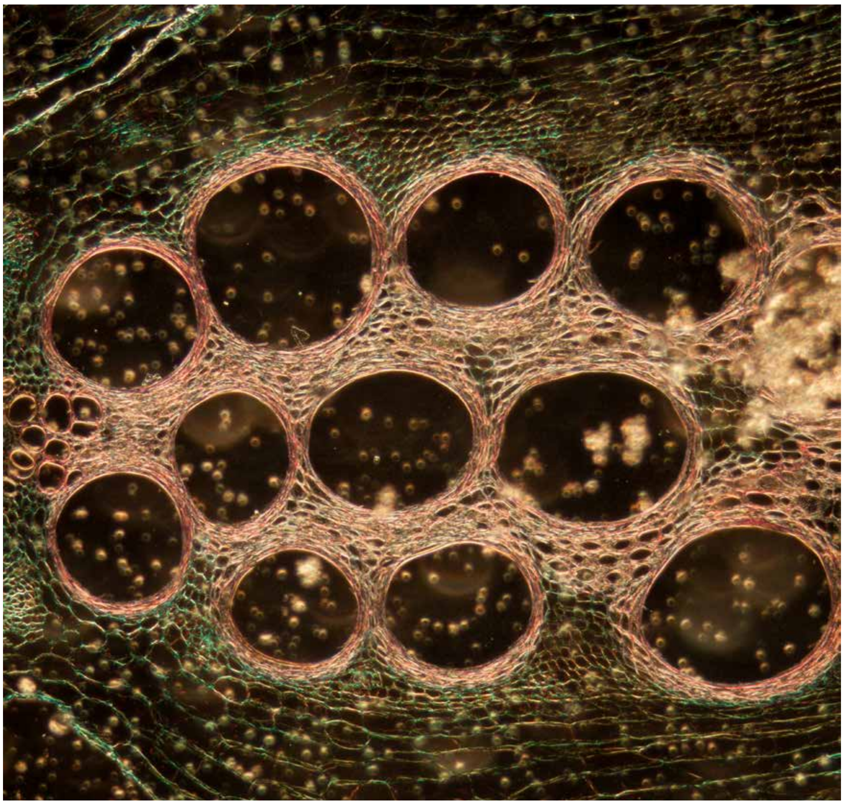
Despite the many advantages of studying the micrometeorology of plants, there are still many aspects of the field that have gone largely unexplored in previous studies. According to Charlotte Coates and Dr Peter Kevan at the University of Guelph in Canada, three of these aspects are particularly important.

Firstly, there is little current knowledge about the heating mechanisms that play out within hollow flowers and stems. These structures contain tiny pockets of air that have been found to behave very differently to the air surrounding them – and are therefore likely to have a strong influence over how plants function.



Secondly, few studies have explored the impact of micrometeorology on plant reproduction. Since many plants grow and thrive in cold environments, they must have evolved advanced solutions to trigger their fertilisation mechanisms – yet these are currently unknown.

Finally, studies into the roles of these air spaces in providing habitats for smaller organisms, particularly insects, are



currently sparse. Since insect damage to many important plant species is growing worldwide, this is a particularly pressing issue. Dr Kevan, Coates, and their colleagues have developed new ways to study these delicate environments.

Developing Imaging Tools

Plant micrometeorology is affected by many different physical properties: including the rates at which plant tissues reflect and absorb sunlight, conduct heat, and change colour. Important information about each of these properties can be gleaned by measuring the surface temperatures of plants, via the varying levels of infrared radiation they emit. Previously, this has been done using cooled thermal cameras that minimise distortions in their images, enabling researchers to study the surface temperatures of individual parts of plants. However, this equipment is bulky and expensive, making it less practical for field research.

Through their research, Coates, Dr Kevan, and their colleagues have developed methods to decrease the error associated with an uncooled thermal camera, which operates at similar temperatures to its surroundings. Instead of a costly cooling system, their approach involves calibrating the uncooled camera at the experiment site to correct the distorted infrared frequencies it detects, allowing them to reproduce reliable images.

By setting up these cameras next to plants, and combining them with extremely precise thermometer readings taken at the time of imaging, the researchers can collect highly accurate data on plant surface temperatures. This technology has now opened up new opportunities to study three the unexplored aspects of plant micrometeorology, which Coates, Dr Kevan and their colleagues first identified.

Greenhouse Effects in Hollow Stems

Hollow stems are important structures in many plants. With mechanical properties comparable to the sturdy poles used in scaffolding, they can be crucial in preventing plants from bending and buckling under their own weight. Yet the air and light contained inside these structures can also display interesting physical properties: as small columns of fluid separated from the surrounding atmosphere, their behaviours are governed by their own unique heating mechanisms. As Coates and Dr Kevan point out, these have been widely overlooked in previous research.

Through a study published in 2018, a team led by Dr Kevan presented new ideas about the processes involved in this heating, and how they interact in complex ways to produce a greenhouse effect – elevating temperatures within hollow stems. The researchers laid out their ideas through a new model, which accounted for the combined influences of surrounding ambient air, radiation from the sun, and a wide variety of both optical and structural properties of the stems. Ultimately, their model shows how each of these effects can both contribute to and be influenced by such a micrometeorological greenhouse effect.

In addition to studying the microgreenhouse effect in relation to heat transfer, the light environment within plants is also important to consider. This is because photosynthesis is dependent on the light environment within plant tissue, rather than outside the tissue. Therefore, the team is also investigating which frequencies of light are present within various hollow-stemmed species, to contribute to our understanding of the microgreenhouse effect. Some of the main species that they study are pumpkins and squash, gerbera daisies, amaryllis and other horticulturally important plants. With contributions from colleagues around the globe, the team's research is helping to create a catalogue of hollow-stemmed plants and their distributions.

Accumulating Heat in Arctic Flowers

Flowers are another type of structure where small-scale heating can be highly

relevant. Like satellite dishes, cup-shaped flowers can focus incident sunlight onto small, concentrated volumes of air, inducing substantial heating.

Through a 2020 study, Dr Kevan assessed how this heating occurred in four common flower species found in the Arctic. In such harsh climates, the ways in which plants grow, feed, reproduce, and interact with herbivores are all strongly influenced by ground temperatures – which remain below freezing for much of the year. Yet in turn, flowers can also influence these temperatures themselves, substantially altering their wider ecosystems.

In his study, Dr Kevan took field surveys of these flowers at three locations in the high Canadian Arctic. His observations revealed that in direct sunlight, air close to ground level could be warmed by up to 6°C when these species were present – clear evidence of another type of microgreenhouse effect. Compared with bare patches of ground, this increased the number of days with above-freezing temperatures at ground level by up to 25%, prolonging the growing season for all plant species surrounding the flowers. As a result, Dr Kevan concluded that these mechanisms are crucial to the survival of many Arctic plants.

Roles in Arctic Plant Reproduction

Coates, Dr Kevan and their colleagues now propose that the passive solar warming effects of stems and flowers together play an important role in plant reproduction. This is particularly true in colder climates, where mechanisms like seed production and fertilisation can only be triggered above certain temperatures. In a 2019 study, Dr Kevan's team assessed how this occurred in another group of flowers. This time, they travelled to the Magadan region in the far north-east of Siberia – an area known for some of the harshest winter temperatures in the northern hemisphere.

Through a field survey, the team investigated the shapes of the flowers and stems of four common plant species in the region. They discovered that hollow stems were over four times more common than solid stems: in contrast, both types are roughly equally as common in most other parts of the world. As a result, the air within the flowers and stems of these plants was generally warmed by between 1 and 6°C compared with their surroundings – and even as much as 10°C in some cases.

In the springtime, where temperatures could still drop to well below freezing, these mechanisms enabled the plants to initiate a wide variety of reproduction mechanisms, ensuring their continued survival.

Providing Habitats for Insects

The mechanisms studied by the team so far may serve the interests of individual plants and the species surrounding them. However, in their latest research, Coates, Dr Kevan, and their colleagues also shed new light on the roles they play in their wider ecosystems. Since many stems and flowers are large enough for insects to crawl inside, they can provide warm, safe environments for them to feed, grow, and reproduce. These microgreenhouse environments are particularly desirable if conditions outside are more extreme.

Through observations taken in a 2020 study, the researchers assessed how several different insect species, from groups including beetles, moths, and sawflies, benefit from the elevated temperatures within flowers and stems. In addition, they showed how they can cause damage to plant tissues through activities like leaf mining, and producing swelling outgrowths named 'galls'. These insights could enable biologists to better understand the environmental roles of plants and insects, and to better assess insect damage in both agricultural crops and ecologically important plants.

Assessing Future Changes

As climate change now threatens to transform the weather patterns experienced by ecosystems worldwide, the research of Dr Kevan, Coates, and their colleagues comes at a critical time. In the coming decades, nowhere on Earth is projected to transform more drastically than the Arctic, where the growth and reproduction of plants, as well as their roles in their wider ecosystems, are intricately connected with their micrometeorology. Therefore, any disruption to typical weather patterns could threaten their survival, as well as the many animals which depend on them.

Elsewhere, climate change is having an increasing impact on insect damage – with warmer temperatures providing better conditions for harmful pests to grow and reproduce. Through a deeper understanding of the many intricate interactions involved in plant micrometeorology and the microgreenhouse effect, they will be able to understand these consequences in more detail. In turn, they could become better equipped to understand how both ecosystems and agriculture can be protected against the coming changes.

Meet the researchers

Dr Peter Kevan
School of Environmental Sciences
University of Guelph
Guelph
Canada

Charlotte Coates
School of Environmental Sciences
University of Guelph
Guelph
Canada

Dr Kevan completed his PhD in Entomology at the University of Alberta in 1970. He became an Assistant Professor at the University of Colorado in 1975, where he worked at the Institute of Arctic and Alpine research until 1983. He joined the University of Guelph in 1982, where he now University Professor Emeritus at the School of Environmental Sciences. Dr Kevan has received numerous awards for his decades of important research, including the Gold Medal of the Entomological Society of Canada in 2005. He is also a Fellow of the Royal Society of Canada. His widely varied research interests include pollination biology, the conservation of beneficial insects, insect thermoregulation, and arctic to tropical ecology.

CONTACT

E: pkevan@uoguelph.ca
W: https://ses.uoguelph.ca/people/peter-kevan

Charlotte Coates is a Masters' student at University of Guelph's School of Environmental Sciences, where she will graduate in 2022. She currently works as a Research Assistant in Dr Kevan's lab, where she has contributed to projects including research into plant temperature regimes; training research assistants in plant surveying; and executing pest management experiments. Coates has earned a number of awards for her work so far, including the MacSon Entrance Graduate Scholarship at Ontario Agricultural College – which she received for her promising research potential in the field of conservation.

CONTACT

E: coatesc@uoguelph.ca
W: https://www.researchgate.net/profile/Charlotte-Coates-3

FUNDING

This project is part of the Accelerating Green Plant Innovation for Environmental and Economic Benefit Cluster and is funded by the Canadian Ornamental Horticulture Alliance (COHA-ACHO) and by the Government of Canada under the Canadian Agricultural Partnership's AgriScience Program.

The researchers also acknowledge support from the Natural Sciences and Engineering Research Council of Canada (Individual Discovery Grant No. RGPIN-2018- 04820 to PK).

FURTHER READING

RA Byerlay, C Coates, AA Aliabadi, PG Kevan, In situ calibration of an uncooled thermal camera for the accurate quantification of flower and stem surface temperatures, Thermochimica Acta, 2020, 693, 178779.

PG Kevan, C Coates, PN Silva, M Larson, Warm & Comfortable within Hollow Stems, Leaf-mines and Galls: Little known habitats for Entomologists & Botanists to explore, Newsletter of the Biological Survey of Canada, 2020, 39, 11.

PG Kevan, Heat accumulation in hollow Arctic flowers: possible microgreenhouse effects in syncalyces of campions (*Silene* spp. (Caryophyllaceae)) and zygomorphic sympetalous corollas of louseworts (*Pedicularis* spp.(Orobanchaceae)), Polar Biology, 2020, 43, 2101.

CJ van der Kooi, PG Kevan, MH Koski, The thermal ecology of flowers, Annals of Botany, 2019, 124, 343.

PG Kevan, EA Tikhmenev, P Nunes-Silva, Temperatures within flowers and stems: possible roles in plant reproduction in the north, Bulletin of the NorthEastern Science Centre of the Russian Academy of Sciences, Magadan, Russia, 2019, 1, 38.

PG Kevan, P Nunes-Silva, R Sudarsan, Short communication: thermal regimes in hollow stems of herbaceous plants—concepts and models, International Journal of Biometeorology, 2018, 62, 2057.

NEW APPROACHES FOR INCREASING WOODLAND GROWTH

Understanding the factors that affect woodland growth can help researchers to develop sustainable forest management practices. This will ensure that society's needs for forest products such as timber and pulp can be met, while also increasing carbon capture and providing important ecosystem services. Previous studies attempting to determine methods for achieving enhanced growth are inconsistent, leading to misconceptions among researchers and forest managers. **Dr Chao Li** and his team at the Canadian Forest Service aim to solve this problem by showing that a phenomenon called 'compensatory growth' can increase overall forest growth in the long-term. Through providing an enhanced understanding of compensatory growth and the factors affecting it, the forestry industry will be better equipped to meet increasing market demands, while also protecting the environment for future generations.

Understanding Forest Productivity

Human activity has led to increased demand for forestry products such as timber and pulp. If a forest cannot grow fast enough to meet these demands, problems can arise in the consumer market. Climate change and biodiversity loss are also becoming increasingly serious issues, meaning that it is now more important than ever before to maximise woodland growth in actively managed forests.

'Forest productivity' is a feature of individual units in a forest, which are called 'stands'. Forest productivity is commonly defined as the whole volume of wood in a stand. However, some researchers prefer to think of it as a yearly increase in a stand's wood volume. These varying definitions of forest productivity can cause inconsistencies and misconceptions amongst forestry professionals.

Gaining a more consistent and deeper understanding of forest productivity would allow such professionals to identify ways to increase the growth of their forests. By doing so, they would be able to increase future timber production and foster sustainable forest management. Additionally, increasing forest productivity could also aid the fight against climate change, because as they grow, trees absorb and store atmospheric carbon dioxide – the primary driver of global climate change.

Dr Chao Li and his colleagues at the Canadian Forest Service have been investigating the conditions needed to enhance the future growth of forests. Their work has resulted in an enhanced understanding of forest productivity and how to increase it, allowing foresters to meet consumer demands while also protecting the environment.

Thinning and Compensatory Growth

In a study published in 2018, Dr Li's team investigated a forestry practice known as pre-commercial thinning, and explored whether this method, alongside fertiliser applications, can be used to enhance forest productivity.

Pre-commercial thinning involves cutting down some younger trees as a forest grows. This is performed because trees within a forest start to compete for resources such as light, space and nutrients as they grow larger, resulting in some trees dying. By thinning the forest of its younger trees, the remaining trees can enjoy increased resources, allowing them to grow much more quickly.

Although the individual remaining trees grow much faster after a thinning treatment, it was unclear how this practice affects the productivity of a forest stand as a whole. Dr Li explains that this gap in our knowledge is due to the slow growth of trees and the scarcity of long-term research trials, which has meant that studies evaluate the response of a forest for a relatively short period after thinning treatments.

'To better support forest management decisions, we must fully evaluate whether pre-commercial thinning results in long-term advantages in forest growth relative to un-thinned sites,' he says. 'There are differing results in the literature, where inconsistent and even controversial results were obtained from different long-term thinning trials: some showed reduced forest productivity as a result of thinning, but others indicated increased forest productivity.'

To resolve this issue, Dr Li and his colleagues wished to find out whether the total volume of wood within a forest stand that had undergone pre-commercial thinning could match with – or even surpass – that of an un-thinned stand. The team refers to this phenomenon as 'compensatory growth'. If thinning does lead to compensatory growth, they also wanted to understand the conditions under which it would happen, and how long it would take under various scenarios.

In their study, the researchers were able to reach beyond the usual short observation periods by revisiting a project that had been initiated by the Canadian Forest Service in the 1970s and is now cooperatively managed by BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development. This initiative, called the Shawnigan Lake Project, focused on an area of 50 hectares, where Douglas-fir trees had been planted in 1948. In the 1970s, researchers had divided the forest into different study treatments. They then performed heavy thinning in some plots, light thinning in others, and no thinning in the remaining plots. In each plot, they also either applied a small or large amount of nitrogen fertiliser, or no fertiliser. In this way, the researchers achieved nine different unique combinations of conditions in their study plots.

Although the growth of trees in these plots had been measured in 2012, 40 years after the Shawnigan Lake Project had begun, the data had not yet been fully analysed. Dr Li wished to explore these measurements in depth to uncover the best combination of conditions for achieving maximum forest productivity.

His team's analysis showed that under the same fertilisation regime, there were no significant differences between the wood volumes of the plots that had been thinned compared to those that

had not. This means that although compensatory growth had allowed the thinned plots to catch up with the un-thinned plots, their wood volumes had not significantly surpassed those of the un-thinned plots.

However, adding fertiliser did seem to make a significant difference. Dr Li's team found that the greatest increases in wood volume had occurred in the plots that had been given a large application of fertiliser 40 years prior. This was closely followed by the plots where a small amount of fertiliser had been applied.

In fact, the plots that had been given a large application of fertiliser alongside light thinning treatments had the largest wood volume. The team was also able to demonstrate that thinning leads to the remaining trees growing much thicker trunks over the study period. Such trees are far more valuable in terms of timber production than trees with slender trunks. Therefore, Dr Li recommends that light pre-commercial thinning is a good option when combined with the use of fertiliser. 'The combination of pre-commercial and fertilisation treatments may represent untapped opportunities for enhancing wood fibre supply in managed forests,' he says.

By investigating results collected on this experiment site in the 1990s, Dr Li and his colleagues found that complete compensatory growth had occurred in most of the thinned plots within 24 years.

Modelling Compensatory Growth

'With all else being equal, such as weather, pests, disease, wildfires and even human pollution, pre-commercial thinning and fertilisation represents an opportunity to enhance timber supply,' says Dr Li. 'Since fertilisation was treated as a surrogate of site quality, the compensatory growth could be expected to speed up with improved site quality.'

In a more recent paper, Dr Li and his colleagues glean insights from hundreds of forestry studies, including those from the Shawnigan Lake Project, to gain a more complete picture of compensatory growth and its impact on overall forest productivity. By investigating the mechanisms that give rise to compensatory growth following a disturbance, such as thinning, they provide forestry professionals with a conceptual framework of this phenomenon, ways to predict it, and its relationship with forest productivity over time.

In this paper, the team also propose the development of a new model that can be used to identify the best conditions to maximize productivity, through the lens of compensatory growth. Such a model would include pre-commercial thinning and other factors that stimulate compensatory growth to predict the growth of surviving trees in a stand.

'Our unified conceptual framework can thus serve as a foundation of developing predictive models of compensatory growth, for taking full advantage of it – as long as we can identify the conditions under which forest productivity could be enhanced,' explains Dr Li.

'The benefits of this new modelling approach is that it provides a powerful framework for evaluating how widespread compensatory growth is among species and forested ecosystems,' he continues. 'The flexible modelling framework allows for inputting species-specific data or inputs to quantify growth responses to various thinning regimes.'

The Work Continues

In their current project, Dr Li and his colleagues are working to further develop this model for predicting growth and yield, based on their conceptual framework of compensatory growth, to understand and predict forest dynamics of stands with different tree species at various geographic locations.

'The direct applications of the model include the determination of optimal spacing in plantation programs, and optimal partial harvest operations leading to maximised management goals,' says Dr Li.

In the future, Dr Li hopes that other researchers and forestry professionals can benefit from his model to determine the best approaches to leverage compensatory growth in their actively managed forests. If compensatory growth can be managed effectively, foresters will be able to enhance woodland growth, timber production, and carbon sequestration. This will help the forestry industry to meet increasing market needs, and may enable improved environmental performance in actively managed forests.

Meet the researcher

Dr Chao Li
Canadian Wood Fibre Centre
Canadian Forest Service
Edmonton, Alberta
Canada

Dr Chao Li was trained in Entomology from Fudan University, and obtained his MSc in Mathematical Ecology from the Chinese Academy of Science, China. Dr Li then went on to earn his PhD in Insect Behavioural Ecology from Simon Fraser University, Canada, in 1993. Upon graduating, he worked as a Canadian Federal Government Laboratory Visiting Fellow at the Northern Forestry Centre in Canada, and as a Research Scientist at the Ontario Forest Research Institute. Over the past 24 years, he has held multiple roles at the Canadian Forest Service, including Knowledge Engineer, Physical Scientist, and Landscape Dynamics Research Scientist at the Northern Forestry Centre and Canadian Wood Fibre Centre. Dr Li has devoted his career to studying the effect of disturbances, both natural and anthropogenic, on forest dynamics, including with the IGBP-GCTE Landscape Fire Working Group on global impacts of fire. By enhancing forest productivity, he hopes to help meet human demands for wood products and contribute to a natural climate solution. Alongside his research, Dr Li also held positions as a Regional Coordinator of IALE-IUFRO Landscape Ecology Working Group (2007–2014) and IUFRO Landscape Ecology Working Party (2000–2014).

Natural Resources Canada
Canadian Forest Service

CONTACT

E: chao.li@canada.ca
W: https://cfs.nrcan.gc.ca/employees/read/cli

KEY COLLABORATORS

Hugh J. Barclay, Canadian Forest Service (retired)
Bernard D. Roitberg, Simon Fraser University
Robert G. Lalonda, University of British Columbia
Shongming Huang, Alberta Agriculture and Forestry

FUNDING

Sustainable Fibre Solution Program of Canadian Forest Service

FURTHER READING

C Li, H Barclay, B Roitberg, R Lalonde, Ecology and prediction of compensatory growth: from theory to application in forestry, Frontiers in Plant Science, 2021, 12, 5 655417.

C Li, H Barclay, B Roitberg, R Lalonde, Forest productivity enhancement and compensatory growth: a review and synthesis, Frontiers in Plant Science, 2020, 11, 575211.

C Li, S Huang, H Barclay, CN Filipescu, Estimation of compensatory growth of coastal Douglas-fir to pre-commercial thinning across a site quality gradient, Forest Ecology and Management, 2018, 429, 308.

THE UNITED STATES NATIONAL VEGETATION CLASSIFICATION: CREATING A COMMON LANGUAGE TO CLASSIFY EARTH'S VEGETATION

In every introductory biology class, students learn the classification system used to catalogue plants, animals, fungi, and other organisms. In this system, the major levels of classification are: domain, kingdom, phylum, class, order, family, genus, and species. The global adoption of this system allows us to create an inventory of the world's species diversity, while accommodating changes based on new discoveries. However, there is no comparable standard system to classify the diverse vegetation, or plant cover, found on Earth. Instead, many land-management groups have created their own classification protocols, hindering collaboration among different agencies. To address this issue in the US, stakeholders have created the United States National Vegetation Classification (USNVC).

Why Classify Vegetation?

People around the world rely on natural and managed vegetation to fuel their day-to-day lives. Myriad local assemblages of different plant species (called plant communities) provide us with food, fibre, clean air, and clean water, among many other valuable resources and services. Additionally, maintaining the rich diversity of organisms on our planet depends on the conservation of these plant communities.

Plant communities are complex and largely resilient to change. However, the accelerating pace of climate change, human introductions of invasive species, and habitat degradation are putting these systems under severe and unprecedented stress. Given how heavily we and other organisms rely on both natural and managed plant communities, urgent action is required to conserve and restore the full spectrum of their diversity.

The first steps toward addressing these issues are describing and classifying the many kinds of plant communities, using concepts referred to as vegetation types. Such fundamental work both supports baseline inventories of vegetation and enables us to monitor how vegetation and site characteristics change with treatments or time. Classification of vegetation is crucial for assessing the status of natural resources, managing invasive species, and setting national policies for resource conservation and management.

CREDIT: Pat Comer.

Because of its complexity and often-continuous variation in space, vegetation presents a unique classification challenge. The plants themselves (which are the primary producers that structure most terrestrial ecosystems), along with soil, climate,

disturbance, and geography, are useful traits for classifying vegetation. To satisfy different needs of stakeholders for detail, the hierarchical structure of the USNVC provides eight levels of specificity regarding these traits. Just like the classification system for organisms, there are fewer broadly defined vegetation types in the upper part of the hierarchy and many more finely defined types in the lower part.

Utilising vegetation classification in the most efficient and effective way requires a standard classification system for all lands, regardless of the responsible management agency. In the 1990s, the Ecological Society of America (ESA), NatureServe (then part of The Nature Conservancy), and federal land management agencies came together to address a significant need: the creation of a systematic vegetation classification system for the US.

As a result, The United States National Vegetation Classification (USNVC) was born, paired with a data standard describing a protocol for collecting and managing vegetation data. The USNVC is now the primary standardised classification system for describing all vegetation types in the US. Its use and implementation by various groups helps to foster inter-agency collaboration and consistent reporting on the nation's vegetation resources.

Given the rapid pace of scientific discovery in a changing world, flexibility is built into the USNVC, allowing changes to be made as scientists and land managers gather more information. Since its establishment in 1998, the USNVC has been adopted for a variety of applications, including natural resource assessment, wildfire management, and conservation planning.

Assessing Natural Resources

Classifying vegetation is particularly important for creating reliable vegetation maps and for supporting inventories that quantify the status of vegetation resources. The USNVC is not only important for assessing the status of natural resource conditions (such as timber and biofuels) and ecosystem services (such as water filtration), but also for helping conservation biologists protect habitat for threatened species.

Since the 1990s, the US National Park Service (USNPS) has used the USNVC to develop accurate, fine-scale vegetation maps to support natural resource management and conservation in US National Parks. For example, the USNPS recently completed the mapping of the Appalachian Trail, which runs through twelve states, using the USNVC. This consistent standard allowed the USNPS to collaborate effectively with adjoining agencies to support natural resource management in areas that border the Appalachian Trail but are managed by other agencies.

The California Department of Fish and Wildlife used the USNVC to assess the state of the rare Mendocino Cypress Woodlands in California. Land managers within that program mapped existing Mendocino Cypress Woodland stands using the USNVC and then related the presence of the stands to certain soil types known to support the trees. By combining the mapping effort with results of soil surveys and knowledge about species biology, the team determined which areas supported the trees before human settlement. As a result, they estimated that there was a 20 to 44% loss of these sensitive woodlands due to agricultural and human development. This information now helps land managers pinpoint areas where the Mendocino Cypress Woodlands may be declining because of habitat loss, allowing for more directed and effective conservation action revolving around increasing suitable habitat for these rare woodlands.

Finally, the USNVC can also be used to assess the condition of natural resources, including timber. For example, the US Forest Service's (USFS) Forest Inventory and Analysis Program (FIA) reports and distributes data about forest resources across the US. The FIA has linked its data with the USNVC classification levels, improving the USFS's ability to monitor the status and condition of both plantation and natural forests, levels of invasive species, stand structure (young forests to old growth), and wood harvesting, by forest type, by region, and across the nation.

Fire Management

One of the most successful applications of standardized vegetation-based classification has been in national-scale vegetation mapping in support of wildfire management. In many parts of the US, the wildfire season has grown longer, and the fires have become more destructive and difficult to manage, due to the effects of climate change. Effectively preventing and managing wildfires in these longer, more volatile fire seasons requires a strategic understanding of the status of wildfire fuels, such as dry vegetation.

Since 2002, integrated ecological classifications, including the USNVC, have been critical tools of the LANDFIRE (Landscape Fire and Resource Management Planning Tools) program, a partnership among wildland fire management programs of the US Forest Service and the US Department of the Interior. Other partners include The Nature Conservancy, US Geological

A prescribed fire.
CREDIT: Thomas Wentworth.

Survey, and NatureServe. LANDFIRE produces data that describe existing vegetation types and their structure, biophysical settings, disturbances, seasonal products, wildfire fuels, and fire regimes across the US. One of the main goals of LANDFIRE is to provide agency leaders with the information they need to manage fire risk.

To achieve this goal, LANDFIRE uses a standardized classification approach to define its map legends in support of wildland fire management, allowing for the creation of dynamic models and high-resolution maps. In 2016, the USNVC was included in the LANDFIRE vegetation map in order to further define the map classes. These maps can be used for a variety of ecological and wildfire management applications. For example, by integrating vegetation maps with a database of protected lands of the US, land managers have access to map data that allow them to assess wildfire risk in lands that lie in or adjacent to protected areas, facilitating improved fire-related and land-management decisions.

Conservation Assessment and Planning

Understanding what vegetation types exist and where they occur is essential to planning for the conservation of the organisms that rely on particular vegetation types. In some cases, USNVC map units can be related to habitat suitability for species at risk of extinction.

Salt Marsh Harvest Mice.
CREDIT: William Thein.

For example, when assessing the status of the federally endangered Salt Marsh Harvest Mouse in the Suisun Marsh of California, researchers needed a better understanding of the habitat requirements of this sensitive species. A research team mapped the habitat of the mice to units of the USNVC and then used this information to track changes in the potential habitat that could support the mice. Over the course of several years, habitat change was monitored to determine if Suisun Marsh was providing less critical habitat for the mice than it had previously.

The USNVC has also been used by federal and state land management agencies to assess how much of a particular vegetation type lies within protected areas. Known as gap analysis, this approach intersects a vegetation map with the boundaries of protected areas to measure the amount of each mapped vegetation type that falls within the current conservation network. In addition to understanding which types are under-represented in the network, this analysis also identifies who owns and manages lands supporting under-represented types and where there are opportunities for restoration and additional conservation action. This kind of inter-agency collaboration is crucial for assessing progress toward protecting plant communities. It also helps in identifying specific targets for conservation across the US and demonstrates the ability of the USNVC to foster such collaboration to address the nation's conservation needs.

The Need for an International Standard

Before the creation and implementation of the USNVC, land management groups in the US were classifying vegetation using different standards. However, the geographic distributions of vegetation types are not constrained by agency, state, or country borders.

In the US, streamlined communication among land management agencies is more crucial than ever, necessitating the creation of a federal vegetation classification standard that can be used by anyone. The USNVC is the answer to this need, offering a hierarchical system of vegetation classification and providing a common language for the effective management and conservation of vegetation in the US.

Given the global scope of the activities that vegetation classification supports, such as natural resource assessment, wildlife monitoring, and conservation planning, it is important to place US vegetation types within a global context. This need is being met through USNVC partner collaborations, including the Canadian National Vegetation Classification and NatureServe's International Vegetation Classification, which currently extends across the Americas and around much of the globe. Through these and other global initiatives, scientists and land managers can now consider vegetation types across their entire range. Examples include the temperate rainforest that spans the west coast of North America from California to British Columbia and southeast Alaska and the Sonoran Paloverde - Mixed Cacti Desert Scrub that extends from the US state of Arizona southward into the Mexican state of Sonora. The USNVC has been instrumental in fostering these international collaborations, bettering all nations' abilities to describe, manage, and protect their natural resources.

About the USNVC

CREDIT: Pat Comer

The United States National Vegetation Classification (USNVC) is the federal standard and only comprehensive vegetation classification system in the US. The USNVC is supported by a formal partnership among the federal agencies, the Ecological Society of America (ESA), and NatureServe, working through the Federal Geographic Data Committee (FGDC) Vegetation Subcommittee. Primary signatories include the US Forest Service, the ESA, NatureServe, and the US Geological Survey Core Science Systems (USGS/CSS).

CONTACT

W: www.usnvc.org

MEMBERS

NatureServe (NS)
Ecological Society of America (ESA)
US Department of Agriculture (USDA)
- Forest Service (FS) – Chair
- National Agriculture Statistical Service (NASS)
- Natural Resources Conservation Service (NRCS)

US Department of Commerce (DOC)
- National Oceanic and Atmospheric Administration (NOAA)
- National Marine Fisheries Service (NMFS)

US Department of Defense (DOD)
- US Army Corps of Engineers (USACE)

US Department of the Interior (USDI)
- Bureau of Land Management (BLM)
- Fish and Wildlife Service (FWS)
- National Park Service (NPS)
- US Geological Survey (USGS)

Environmental Protection Agency (EPA)
National Aeronautics and Space Administration (NASA)

FURTHER READING

A McKerrow, A Davison, M Rubino, D Faber-Langendoen, D Dockter, Quantifying the representation of plant communities in the protected areas of the U.S.: An analysis based on the U.S. National Vegetation Classification Groups, Forests, 2021, 12, 7, 864.

T Keeler-Wolf, T Hickson, R Yacoub, MJ Colletti, Classification and mapping of Mendocino Cypress (Hesperocyparis pygmaea) Woodland and related vegetation on oligotrophic soils, Mendocino and Sonoma Counties, California, 2019, Classification and Mapping Program, California Department of Fish and Wildlife, Sacramento, CA.

R Boul, D Hickson, T Keeler-Wolf, MJ Colletti, A Ougzin, 2015 vegetation map update for Suisun Marsh, Solano County, California. A report to the California Department of Water Resources, 2018. Prepared by: Vegetation Classification and Mapping Program Biogeographic Data Branch, California Department of Fish & Wildlife.

D Faber-Langendoen, K Baldwin, RK Peet, D Meidinger, E Muldavin, T Keeler-Wolf, J Carmen, The EcoVeg approach in the Americas: U.S., Canadian and International Vegetation Classifications, Phytocoenologia, 2018, 46, 2, 215.

S Franklin, P Comer, J Evens, E Ezcurra, D Faber-Langendoen, J Franklin, M Jennings, C Josse, C Lea, O Loucks, E Muldavin, R Peet, S Ponomarenko, D Roberts, A Solomeshch, T Keeler-Wolf, J Van Kley, A Weakley, A McKerrow, M Burke, C Spurrier, How a national vegetation classification can help ecological research and management, Frontiers in Ecology and the Environment, 2015, 13, 4, 185.

D Faber-Langendoen, T Keeler-Wolf, D Meidinger, D Tart, B Hoagland, C Josse, G Navarro, S Ponomarenko, J-P Saucier, A Weakley, P Comer, EcoVeg: A new approach to vegetation description and classification, Ecological Monographs, 2014, 84, 4, 533.

MD Jennings, D Faber-Langendoen, O Loucks, RK Peet, D Roberts, Standards for associations and alliances of the U.S. National Vegetation Classification, Ecological Monographs, 2009, 79, 2, 173.

FGDC [Federal Geographic Data Committee], Vegetation Classification Standard, FGDC-STD-005, Version 2, Washington, DC, USA, 2008.

IDENTIFYING EFFECTIVE STRATEGIES TO PROTECT LOUISIANA'S PRECIOUS WETLANDS

The Louisiana coastal zone is the fastest-eroding wetland in the US. This region is home to a variety of vitally important fish species for local fishing industry and ecosystems, which are currently under threat. Conservation schemes have been proposed under the 2017 Louisiana Coastal Master Plan in an attempt to preserve coastal habitats and their inhabitants. **Dr Kim de Mutsert** of the University of Southern Mississippi and her colleagues use simulations to reveal how different management strategies will affect fish and shellfish up to 50 years from now.

Coastal Erosion in Louisiana

Louisiana is one of the most rapidly eroding states in the US. In fact, 90% of coastal wetland loss in the country occurs in this state – at almost 23 square miles per year between 1932 and 2016. This is predicted to rise to around 35 square miles per year by the early 2050s.

'The Louisiana coast suffers from a land-loss problem, where coastal wetlands are sinking and eroding away until open water remains,' explains Dr Kim de Mutsert from the University of Southern Mississippi. As 40% of wetlands in the US are found in Louisiana, conservation is of great importance for protecting the local environment and its species.

Rising sea levels, fragmentation (where channels that are dug for the oil and gas industry break up habitats into smaller sections), and the construction of levees on rivers are mainly to blame for the rapid disappearance of coastal wetlands.

Levees are artificially raised riverbanks, which prevent areas next to the river from flooding. They are incredibly beneficial as a form of flood protection – especially when settlements have been built on floodplains. However, levees on the Mississippi river in Louisiana prevent valuable sediment from reaching the important coastal wetlands, which means that eroded land is not replenished. Levees also prevent nutrients and freshwater from reaching these wetlands, which has resulted in shifts in the communities of aquatic species towards species that prefer more salty environments.

The Louisiana Coastal Master Plan

The Louisiana Coastal Master Plan (CMP) describes strategies to maintain and regenerate these coastal areas, which are being eroded and degraded by human activity. The plan compiles scientific research and engineering approaches to establish the best possible conservation strategies along 800 square miles of coastline. The aim of the CMP is simply to protect

coastal land, its species, and the communities that depend on them, through a combination of strategies that maintain and restore coastal land, with freshwater diversion schemes standing at the forefront.

Dr de Mutsert is working with other researchers to evaluate the effects of various restoration approaches on fish and shellfish using models. One of their main criteria is how well a given strategy will help to restore wetlands, which

will have knock-on effects on aquatic species populations.

Dr de Mutsert has been involved with multiple projects that have contributed to the CMP, including modelling and comparing outcomes of potential restoration projects. The simulations run to 20 and 50 years into the future and are compared with a scenario in which no restoration action is taken. The models also test combinations of projects in order to find the optimal conservation strategy for each area.

'Restoring the coast has the potential to change the biomass and distribution of economically and ecologically important fisheries species,' says Dr de Mutsert. 'However, not restoring the coast may have negative impacts on these species due to the loss of habitat.'

The study addresses the issue on a landscape-wide scale over 50 years – a novel insight that simulates impacts on multiple aquatic species, and considers environmental factors and fishing. Specifically, Dr de Mutsert's research focuses on the effects of sediment diversion schemes, which involve creating openings in levees to divert freshwater, sediment, and nutrients to wetlands and estuaries. Prior to Dr de Mutsert's research, simpler models were used that do not simulate species interactions and focus on the suitability of the habitat only.

The Ecopath with Ecosim Model

Dr de Mutsert and her fellow researchers use the Ecopath with Ecosim (EwE) modelling software, which was developed to investigate food webs, fisheries, and ecosystems. EwE has three components: Ecopath, a snapshot of the ecosystem at a particular period of time; Ecosim, to simulate how a policy might influence a system over time; and Ecospace, which adds a spatial component to the model.

The model was initially calibrated in Ecosim on one section of the Louisiana coast, the Mississippi River Delta. This area was scaled up to cover the entire Louisiana coast in 2015 in order to support decision-making for the 2017 CMP. The smaller area was used again in Dr de Mutsert's most recent 2021 paper, where she simulated the effects of the CMP.

The model considers environmental characteristics that may influence the biomass of aquatic species, such as the extent of the marsh edge, water temperature, salt content, the availability and deposition of sediment, and the nutrient concentration in the water. These factors change over time in Dr de Mutsert's model in order to replicate a changing climate and the resulting change in biomass and distribution of species.

Using the model, her team made projections over timescales of 20 and 50 years, as well as some higher-resolution projections over one to five years. In one of Dr de Mutsert's earlier research papers, she points out that many differences between schemes become much more apparent over longer periods of time. By running simulations over 20 and 50 years, policy makers

involved in the Louisiana CMP gain a reliable projection of how different actions are likely to impact aquatic species and can see how these outcomes diverge over longer periods of time.

How Will the CMP Impact Coastal Environments?

A future with the Louisiana CMP appears to have generally positive outcomes for coastal habitats and fish populations compared to a scenario where no conservation strategy is put in place. Dr de Mutsert's research focuses on how the CMP will impact aquatic species – the results of which are a little more intricate.

Different species live in different habitats along the Louisiana coastline, and therefore restoration strategies have varying impacts in different areas. For example, the biomass of blue crabs and black drum fish will be lower in the Birdsfoot Delta region when modelled under the proposed CMP scenario, as opposed to where no action is taken. Meanwhile, biomass of brown and white shrimp is projected to be the same or higher in all basins under the same scenario, while spatial distribution changes. Policy makers therefore need to respond to the outcomes of CMP strategies, such as by supporting fishers with the resources they need to continue fishing when species distributions change.

This can be easily explained by the preference of species for a particular type of environment, such as saltier water. When modelling scenarios where more water is diverted to wetlands from freshwater rivers, the populations of species that favour salty water moved or decreased while the number of those that prefer more freshwater environments increased. There will therefore be evident trade-offs between species when implementing restoration schemes.

Another complexity that has been investigated by other research is that, while an increase in nutrient flow from river diversions is an essential factor for increasing biomass in coastal wetlands, the associated increase in water-suspended sediment and nutrients – causing eutrophication in some areas – could block sunlight from reaching plant species at the sea bed. In other areas, however, an increase in nutrients will increase the biomass of some species. The likely result from this is that some species that are able to move will be redistributed, while the biomass of other species that are static will be reduced. Furthermore, an increased influx of nutrient-rich freshwater may weaken the plant root structure, making the wetlands more susceptible to erosion during storms.

Dr de Mutsert's research will be exceptionally important to policy makers and resource managers who will be able to use the information to manage and adapt local ecosystems in response to CMP schemes.

The Mid-Barataria Diversion

Recently, Dr de Mutsert and her collaborators investigated the potential effects of one particular CMP tool, the Mid-Barataria sediment diversion from the Mississippi River. Sediment models feeding into the ecosystem models from Dr de Mutsert's 2017 and 2021 papers have shown that in the absence of this proposed diversion, significant negative changes would be witnessed in the coming decades, with serious damage to Louisiana's coast, its ecosystems, and the local economy.

'The Mid-Barataria diversion gives us a chance to keep Barataria Bay from disappearing rapidly,' says Dr de Mutsert. 'Perhaps surprisingly, most living marine resources are better off when the diversion is built compared to a future without it.' In a letter addressed to policy makers, Dr de Mutsert and 54 other signatories express their overwhelming support for the proposed scheme.

Next Steps

Dr de Mutsert's research enables decision makers to understand projected successes and shortfalls of CMP schemes before putting them in place, and can offer advice to determine which strategy, or combination of strategies, are likely to be most beneficial for each area. Changes can also be made prior to implementation to ensure the most beneficial outcome for both local communities and wildlife.

Meet the researcher

Dr Kim de Mutsert
Division of Coastal Sciences
School of Ocean Science and Engineering
University of Southern Mississippi
Ocean Springs, MS
USA

Dr Kim de Mutsert earned her PhD in Oceanography and Coastal Sciences in 2010 from Louisiana State University, after completing an MS in Biology at the University of Amsterdam. She then remained at Louisiana State University until 2011 as a postdoctoral researcher, before moving on to become Assistant Professor at George Mason University. Dr de Mutsert now works as Assistant Professor in the Division of Coastal Sciences of the School of Ocean Science and Engineering at the University of Mississippi and is Affiliate Faculty at George Mason University. She specialises in coastal and estuarine fish ecology, particularly looking at human and environmental impacts on abundance, structure, and dynamics of fish communities, and her work has been cited more than 600 times. During her career, Dr de Mutsert has developed models to simulate how environmental changes affect fish and fisheries. She has been working on projects pertaining to coastal restoration for over 10 years and has published a substantial quantity of research on the topic.

CONTACT

E: kim.demutsert@usm.edu
W: demutsertlab.com
@demutsertlab

KEY COLLABORATORS

Kristy Lewis, University of Central Florida
Joe Buszowski, Ecopath International Initiative
Steve Brandt, Oregon State University
Dave Chagaris, University of Florida

FUNDING

Louisiana Coastal Protection and Restoration Authority
NOAA National Centers for Coastal Ocean Research
NOAA RESTORE Science Program
National Academy of Sciences Gulf Research Program

FURTHER READING

K de Mutsert, KA Lewis, ED White, J Buszowski, End-to-End Modeling Reveals Species-Specific Effects of Large-Scale Coastal Restoration on Living Resources Facing Climate Change, Frontiers in Marine Science, 2021, 8, 624532.

K de Mutsert, K Lewis, S Milroy, J Buszowski, J Steenbeek, Using ecosystem modelling to evaluate trade-offs in coastal management: Effects of large-scale river diversions on fish and fisheries, Ecological Modelling, 2017, 360, 14.

K de Mutsert, JH Cowan Jr., CJ Walters, Using Ecopath with Ecosim to Explore Nekton Community Response to Freshwater Diversion into a Louisiana Estuary, Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science, 2012, 1, 104.

THE UNIVERSITY OF SOUTHERN MISSISSIPPI

GENETIC RESCUE SAVES SPECIES FROM EXTINCTION

Human impacts on plant and animal populations can be striking. Landscape-level transformation of pristine habitats means less room for plants and animals and the inevitable decline and extinction of many species. However, human impacts can also act on threatened species in less obvious ways, including on their genomes. Because of shrinking populations, many plants and animals are highly inbred, tipping the scales in favour of extinction. **Dr Alexandra (Sasha) Pavlova** and **Professor Paul Sunnucks** at Monash University, Australia, are at the forefront of applied research that seeks to increase genetic diversity to help populations rebound.

Inbreeding Depression

When a species' habitat shrinks, its populations inevitably decline. Those that persist in remaining islands of habitat have no choice but to breed with related individuals. Inbreeding depression describes the reduced survival and fertility of the offspring of these related individuals. As populations contract, inbreeding depression typically grows to a point where usual conservation measures, such as habitat restoration, have greatly reduced effectiveness. At this point, we must treat this key cause of declining populations – a lack of genetic diversity.

The most effective solution to inbreeding depression is 'genetic rescue', a tool that makes new genetic material available by increasing gene flow into a population. These actions improve populations' genetic diversity, providing them with a better chance of adapting to new stressors such as climate change and habitat loss. In practice, genetic rescue typically involves allowing inbred individuals from one population to mate with individuals in another. When a population is the last of its kind, this may entail using distinct 'new blood', such as members of a different subspecies.

Genetic rescue is under-utilised, despite being relatively inexpensive and highly effective. This low uptake is a result of insufficient understanding of the risks and benefits of genetic rescue versus the risk of doing nothing. Although in rare cases genetic management can result in reduced population growth and loss of distinctiveness, such risks can often be mitigated by appropriate choice and number of breeders. Meanwhile, left unchecked, inbreeding depression and loss of genetic diversity will often lead to extinction. Appropriate consideration of the risks and benefits of genetic rescue should produce a management strategy to maximise the chance of a species persisting into the future.

Dr Sasha Pavlova and Professor Paul Sunnucks at Monash University are two of the most active researchers in the field of genetic management. They have worked for years to establish critical methods and theories to save endangered species, and have collaborated with conservation managers to road-test solutions to genetic problems in a 'learning-by-doing' approach. According to Professor Sunnucks, the tools they and their community of like-minded conservationists have developed 'can make the difference between persistence and extinction'.

In a recent project, the two researchers teamed up with Australian wildlife management agencies to evaluate whether genetic rescue can help a range of endangered animals and plants. Along with directly informing restoration efforts for five endemic species, the team's ambitious project set out to demonstrate the effectiveness of genetic rescue under on-ground conservation management settings, with the hope of increasing its accessibility and uptake as part of the conservation 'toolkit' alongside more traditional techniques.

The Critically Endangered Helmeted Honeyeater

The Helmeted Honeyeater is the bird emblem of Victoria, Australia. Named for its bright yellow 'helmet' of head feathers, the birds were once common through swampy habitat in southern Victoria, but are now found only in Yellingbo Nature Conservation Reserve after they lost over 99% of their habitat to human encroachment. By 1989, only 50 birds remained.

Over recent years, the team's work led by Dr Katherine Harrisson evaluated the genetic health of the birds to assess whether genetic rescue could supplement existing large-scale conservation efforts. On the back of 30 years of fieldwork led by Bruce Quin

The Helmeted Honeyeater. CREDIT: Peter Menkhorst.

Juvenile Leadbeater's Possum. CREDIT: Dan Harley

of the Victorian Department of Environment, Land, Water and Planning (DELWP), they were able to apply the rarely achieved 'gold standard' measure of genetic fitness – reproductive output over individual lifetimes in the wild. The severity of the inbreeding depression detected was shocking: lifetime reproductive output of the most inbred birds was only 10% that of the least inbred ones – enough to cause extinction within decades.

To test whether it might be possible to reduce inbreeding by managing birds' mating choices in the wild, in 2021 the team developed an innovative method devised by PhD candidate Diana Robledo-Ruiz. Sadly, the answer was 'no'. So, given that genetic rescue must be part of the solution to prevent extinction of this unique bird, where will genetic 'refreshment' come from?

The Helmeted Honeyeater posed an increasingly common conundrum: because the only remaining population of its kind is heavily inbred, researchers had to look to other subspecies as a source of additional genetic variation. Colleagues at Zoos Victoria crossed Helmeted Honeyeaters with the most closely related of the other three subspecies of Yellow-tufted Honeyeater. Because the mated birds were unrelated, their offspring had greater genetic diversity, allowing them to overcome the harmful effects of inbreeding. These crossed birds are faring well in the wild at Yellingbo, and in 2021 a second population was established, including some of the 'genetically diverse' birds.

In collaboration with DNA Zoo and others, led by Diana Robledo-Ruiz the team published an unusually high-quality genome sequence and genetic map of the Helmeted Honeyeater in 2022. Together with genome sequences of dozens of birds, these resources are being applied in sophisticated analyses to reconstruct population histories and to understand how genetic variation can be managed to prevent the extinction of Helmeted Honeyeaters. Monitoring whether and how genetic rescue heals the genomes of Helmeted Honeyeaters will allow management actions to be adjusted where necessary.

In addition to funding from diverse sources, these efforts are possible only through the sustained commitment, energy and goodwill of many stakeholders – including DELWP, Zoos Victoria, the Helmeted Honeyeater Recovery Team, and community groups, notably The Friends of the Helmeted Honeyeater.

The Lowland Leadbeater's Possum

The Helmeted Honeyeater isn't the only critically endangered animal at Yellingbo Nature Conservation Reserve. It is accompanied by a tree-dwelling mammal – the only remaining lowland population of Leadbeater's Possum. The Yellingbo populations of these two species share an unfortunate statistic: the lowland Leadbeater's Possum has also lost more than 99% of its habitat in the last 200 years through human activities, and fewer than 30 individuals now remain in the world.

Based on 20 years of field data collection driven by Dr Dan Harley of Zoos Victoria, an analysis led by Dr Joe Zilko demonstrated appreciable inbreeding depression problems in lowland Leadbeater's Possum. Computer modelling showed that these problems would drive extinction in the immediate future. Luckily, there are some potential source populations of this critically endangered species to cross with the declining Yellingbo population. Field trials are underway on establishing a new population with 'pioneers' from Yellingbo and other populations, towards producing offspring of high viability and fecundity to secure the fate of this important mammal.

Macquarie Perch: A Threatened Fish

The Macquarie Perch is a freshwater fish endemic to Australia. Like many freshwater fish, the Macquarie Perch has faced tremendous and diverse stressors including overfishing, habitat degradation and changes in river conditions resulting from dam construction. Over a century or so, these fish have been forced to retreat into isolated headwater populations that cannot connect with each other and are mostly too small and genetically unhealthy to be sustainable.

Macquarie Perch. CREDIT: Zeb Tonkin.

Button Wrinklewort. CREDIT: Steve Sinclair

A 2017 paper focused on the perch led by Dr Pavlova argued that rather than needing to demonstrate inbreeding depression for every new case, we can instead adequately assess the degree of genetic problems in wildlife by simpler genetic analyses, and anticipate the benefit of genetic rescue by computer simulation. 'Insisting on a demonstration that inbreeding depression occurs in a particular population is impractical and counter-productive, using up valuable time and resources, detracting from getting on with the task of bolstering the health of the population by incorporating genetic management into conservation actions,' says Dr Pavlova. The paper informed the *National Recovery Plan for the Macquarie Perch*.

Over the last decade, DELWP staff headed by Drs Zeb Tonkin and Jarod Lyon have reintroduced a population of Macquarie Perch into restored habitat in the Ovens River in Victoria, where it had previously gone extinct due to habitat degradation. Rather than using founding individuals from a single river source, the team used perch stock including fish with parents from different rivers, bred by Fisheries Victoria's Dr Brett Ingram. Intensive monitoring by DELWP and genetic analyses of the growing population as part of Dr Maiko Lutz's PhD revealed that using multiple sources led to better outcomes for fish survival and reproduction than the typical single-source approach would have. In other words, notions of keeping sources 'pure' may be counterproductive.

Reversing the Decline of Button Wrinklewort

The principles of genetic rescue to repair inbreeding depression and loss of genetic variation are not limited to animals. The Button Wrinklewort, once a common grassland daisy in south-eastern Australia, is yet another example of a species that has lost over 99% of its habitat to human impacts. It now occurs in a few dozen small and isolated populations. Like many plant species, Button Wrinklewort possesses a genetic mechanism to prevent individuals mating with themselves and close relatives. This system works well in large populations, but in small ones, individuals run out of genetically compatible mates, reducing or preventing their breeding. This problem can be rectified by mixing small and isolated populations, restoring the supply of genetically compatible mates.

Applying these concepts, genetic rescue of this species is ongoing, driven by DELWP's Dr Steve Sinclair and Dr John Morgan of La Trobe University. A 2021 paper led by PhD candidate Yael Rodger evaluated genetic relationships among populations of Button Wrinklewort, and their levels of genetic diversity, enabling specific suggestions about which populations should be crossed. Surprisingly, some of the smallest and most isolated populations retain the highest levels of diversity, showing that it is not always best to assume that larger populations have better genetic health.

A Case for Genetic Management

Genetic management is growing in uptake and acceptance. Over the last three decades, scientists such as Dr Pavlova and Professor Sunnucks have aimed to bridge the gap between genetic research and on-ground conservation efforts. As a result of their work with their colleagues from wildlife management agencies, Australia is becoming a leader in using genetic rescue for conservation planning.

In the State of Victoria where Dr Pavlova and Professor Sunnucks are based, the government environment agency DELWP uses genetic management as a mainstream factor in conservation planning, including application of their innovative Genetic Risk Index. There is only a handful of such initiatives worldwide, but growing positive outcomes of genetic rescue provide reason to hope that others will follow.

A global leader in conservation, the International Union for Conservation of Nature, initiated a Conservation Genetics Specialist Group, which, in association with other organisations, has been active in highlighting the critical role of genetic considerations in conservation planning. There is exciting innovation in the private sector too – a great example being the major positive contributions of the not-for-profit organisation Revive & Restore.

Global adoption of genetic management of wildlife can't come quickly enough. According to Professor Sunnucks, 'unless we use genetic rescue as part of properly-funded conservation efforts, we will often simply manage small, isolated populations to extinction'.

Meet the researchers

Dr Alexandra (Sasha) Pavlova
School of Biological Sciences
Monash University
Clayton, Melbourne
Victoria, Australia

Dr Pavlova is an evolutionary biologist passionate about biodiversity conservation. She received a Master's in Zoology from Moscow State University and a PhD in Ecology, Evolution and Behavior from the University of Minnesota. In 2005, Dr Pavlova teamed up with Professor Sunnucks in Australia, where she integrates genetics, evolution and ecology to study how wildlife adapts and persists in the face of human impacts. She uses this knowledge to help her wildlife management collaborators improve outcomes for species of conservation concern.

E: alexandra.pavlova@monash.edu
W: https://sites.google.com/monash.edu/sashapavlova

Professor Paul Sunnucks
School of Biological Sciences
Monash University
Clayton, Melbourne
Victoria, Australia

Professor Sunnucks is a global leader in conservation genetics. After a PhD at University College London and working in one of the world's first conservation genetics groups at the Institute of Zoology, London, Professor Sunnucks migrated to Australia, where he now co-leads a research group with Dr Pavlova using genetic tools to help threatened species recover. Through collaborative scientific papers and books, and advice to diverse stakeholders in biodiversity, Professor Sunnucks works towards more widespread uptake of genetic management of wildlife.

E: paul.sunnucks@monash.edu
W: https://www.monash.edu/science/schools/biological-sciences/staff/sunnucks

KEY COLLABORATORS

Dr Jon Ballou, Smithsonian Conservation Biology Institute; Bridget Baumgartner, Revive & Restore; Matthew Beitzel, Environment, Planning & Sustainable Development Directorate, ACT Government; Anne Buchan, Department of Environment, Land Water and Planning, Victoria; Dr Rohan Clarke, Monash University; Alan Clayton, Friends of the Helmeted Honeyeater; Dr Meaghan Duncan, NSW Department of Primary Industries: Fisheries; Dr Owain Edwards, CSIRO; Professor Richard Frankham, Macquarie University and Australian Museum, Sydney; Dr Ming Han Gan, Deakin University and GeneSEQ; Dr Dan Harley, Zoos Victoria; Dr Katherine Harrisson, La Trobe University; Dr Carolyn Hogg, University of Sydney; Dr Brett Ingram, Fisheries Victoria; Dr Parwinder Kaur, DNA Zoo, University of Western Australia; Dr Andrzej Kilian, DArT P/L; Dr Bob Lacy, Chicago Zoological Society; Meagan Lane, Healesville Sanctuary Helmeted honeyeater keeper; Associate Prof Mark Lintermans, University of Canberra; Dr Jarod Lyon, Department of Environment, Land Water and Planning; Dr Michael Magrath, Zoos Victoria; Dr John Morgan, La Trobe University; Ben Novak, Revive & Restore; Dr Zeb Tonkin, Department of Environment, Land Water and Planning; Bruce Quin, Department of Environment, Land Water and Planning; Dr Katherine Ralls, Smithsonian Conservation Biology Institute; Diana Robledo-Ruiz, Monash University; Dr Steve Sinclair, Department of Environment, Land Water and Planning; Dr Kim Miller, Healesville Sanctuary Life Science Manager; Dr Andrew Weeks, University of Melbourne

FUNDING

Australian Research Council; Department of Biodiversity, Conservation and Attractions, Western Australia; Department of Environment, Land, Water and Planning, Victoria; DArT P/L; Environment, Planning & Sustainable Development Directorate, ACT Government; Helen Macpherson Smith Trust; Holsworth Wildlife Research Endowment/Ecological Society of Australia; Icon Water; Melbourne Water; Parks Victoria; Revive & Restore; Victorian Fisheries Authority/Fisheries Victoria; Zoos Victoria

FURTHER READING

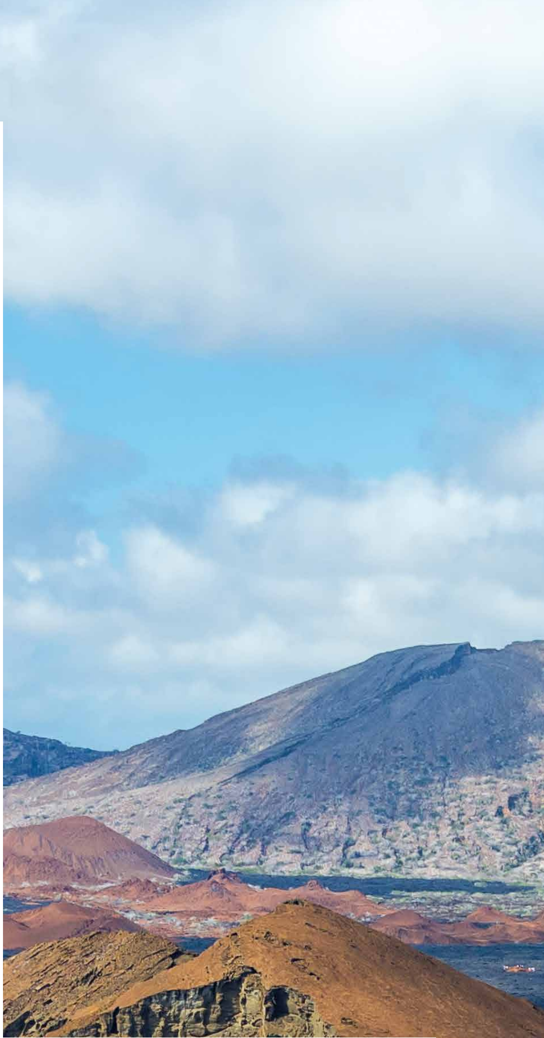
K Ralls, JD Ballou, MR Dudash, MDB Eldridge, CB Fenster, RC Lacy, P Sunnucks, R Frankham, Call for a paradigm shift in the genetic management of fragmented populations, Conservation Letters, 2018, 11, 1-6.

ML Lutz, Z Tonkin, JD Yen, G Johnson, BA Ingram, L Sharley, J Lyon, DG Chapple, P Sunnucks, A Pavlova, Using multiple sources during reintroduction of a locally extinct population benefits survival and reproduction of an endangered freshwater fish, Evolutionary Applications, 2021, 14, 950-964.

KA Harrisson, MJL Magrath, JDL Yen, A Pavlova, N Murray, B Quin, P Menkhorst, KA Miller, K Cartwright, P Sunnucks, Lifetime fitness costs of inbreeding and being inbred in a critically endangered bird, Current Biology, 2019, 29, 1-7.

JP Zilko, D Harley, B Hansen, A Pavlova, P Sunnucks, Accounting for cryptic population structure enhances detection of inbreeding depression with genomic inbreeding coefficients: an example from a critically endangered marsupial, Molecular Ecology, 2020, 29, 2978-2993.

THE GALAPAGOS INITIATIVE: SAVING THE ENCHANTED ISLANDS



The Galapagos Islands are facing increasing danger. Local and global forces – including tourism and climate change – threaten the fragile island ecosystems. The high number of unique plants and animals on the islands means that the loss of a Galapagos species may represent a global extinction event. The Galapagos Initiative, founded by **Dr Stephen Walsh** of the University of North Carolina at Chapel Hill and Dr Carlos Mena of the Universidad San Francisco de Quito, aims to save the Galapagos Islands with an innovative, sustainable strategy combining evidence from key interdisciplinary projects and a robust mapping and modelling program.

Showcasing Evolution on Earth

The astonishing beauty of the Galapagos Islands, with its turquoise and gold beaches and its jagged volcanic landscape, is matched by the islands' incredible marine and terrestrial plant and animal species. Known as a living laboratory, the islands are home to hundreds of 'endemic' species – found nowhere else on Earth. Situated within three different ocean currents, the Galapagos Islands also host a spectacular wealth of marine species.

The 127 islands, islets and rocks making up the Galapagos archipelago were formed through volcanic and geological processes, and are situated around 1000 kilometres off the coast of Ecuador. The bio-physical processes shaping the landscape and the extreme geographic isolation led to the rapid evolution of plants and animals that survived the journey to the islands.

Included in the islands' incredible diversity and endemism are marine iguanas, giant tortoises, the most northern species of penguin, enormous cacti, flightless cormorants, an array of mockingbird and finch subspecies, and even an owl, a flamingo, and a hawk species. It is little wonder then that the incredible diversity on the islands inspired Charles Darwin's theory of evolution – and forever shaped our understanding of life on the planet.

But the precious ecosystems and species of the Galapagos Islands are in peril. Island ecosystems around the world are changing, potentially irreversibly, due to complex social-ecological interactions operating across spatial and temporal scales. Rising ocean temperatures, extreme weather events, sea-level rise, tourism, population migration and development, and invasive species all act – and interact – to threaten the planet's vulnerable islands and their sustainability.

Sea turtle

An increasing number of tourists are visiting the Galapagos Islands to interact with the iconic species and unique terrestrial and marine environments, while the islands' resident population is growing to support the tourist industry. Inevitably, conflicts have emerged between resource conservation and economic development. For example, changes in land use associated with development often degrade viable habitats that support the islands' wildlife. So well-known are these inherent difficulties that they have become known as the 'Galapagos Paradox' – we are quite literally loving the islands to death.

Galapagos Science Center (lower right building) and Community of Puerto Baquerizo Moreno

These issues are overlaid with the ongoing threats imposed by climate change. The impacts of warming temperatures, sea-level rise, and more extreme weather events are complex and difficult to predict – especially so for island ecosystems that often exhibit less resilience than mainland ecosystems. Determining the potential future of the islands, and how to save them, requires an innovative, interdisciplinary approaches that combine an understanding of the linked social, terrestrial, and marine sub-systems and an assessment of alternative tourism and climate change scenarios linked to plausible ecosystem responses.

Building on the long-term commitment of the University of North Carolina at Chapel Hill to researching the Galapagos Islands, Dr Stephen Walsh partnered with Dr Carlos Mena of the Universidad San Francisco de Quito in Ecuador to develop the Galapagos Initiative. The program includes research, education, and community outreach and engagement programs, with a focus on population, health and environment, to better understand the social, terrestrial, and marine sub-systems in the islands and their interactions.

The crowning achievement of the Galapagos Initiative has been the construction of the Galapagos Science Center (GSC), located on San Cristobal Island. The facility, which was officially dedicated in 2011, includes four specialised laboratories covering microbiology and genetics, marine ecology, terrestrial ecology, and spatial analysis and modelling. Projects conducted by the Galapagos Initiative scientists, staff, and students provide evidence that is helping to shape science and conservation strategies for the Galapagos Islands, and could help to conserve other fragile island ecosystems around the world.

Modelling Complex Interactions

The Galapagos Islands are designated as a UNESCO World Heritage Site, a national park, and a marine reserve. The rapid growth of tourism since the 1970s has put the islands under increasing strain. Every year, thousands of tourists flock to the islands to enjoy its natural beauty, and the resident population has grown accordingly to support the tourism industry. In 2019, over 275,000 tourists visited the islands. The resident population tripled in the preceding 15 years, reaching around 35,000 in the same year.

The expanding human population has contributed to over-use of natural resources, replacement of native flora and fauna with invasive species, development into increasingly fragile environments, and a dramatic increase in energy consumption and waste production.

As such, a fundamental question is how many people – both tourists and residents – can the islands support before the environment is severely degraded. Dr Walsh explores this question through the emerging theory of 'biocomplexity'. As he explains, biocomplexity 'conceives the world as consisting of self-organised systems, either reproducing their state through negative feedbacks with their environment or moving along trajectories from one state to another as a result of positive feedbacks.'

'It encompasses the complex interactions within and among ecological systems, the physical systems on which they depend, and the human systems with which they interact,' he adds.

Galapagos penguins

Marine iguanas

Dr Walsh and Dr Mena used this theoretical context to guide the development of two spatial simulation models. Their 'dynamic systems model' examines environmental and human population factors and their interactions, while their 'agent-based model' examines how the decisions made by individuals relate to large-scale system changes. For example, the decision to switch from fisheries-based employment to tourism-based employment is made by individuals, but contributes to the overall growth of the resident population.

Their findings suggest that the islands are close to reaching their limit. 'If tourism continues to grow at the pace of the past two decades, depending on the type of growth, in a few years there will be limited to no open space and amenity resources to ensure that every tourist visiting the Galapagos experiences nature tourism at a high standard of quality,' explains Dr Walsh.

Over time, most of the islands' tourism business has been dominated by external companies, with only a small proportion of the profits and high-level tourism jobs benefitting local residents. This is a source of social inequality. Through his model, Dr Walsh explored alternate strategies that allow economic development to occur in sustainable ways. 'If residents retain control of business opportunities and high-paying tourism jobs, the industry may become the envisioned bridge to a robust and satisfying livelihood with lower environmental impacts for many more residents,' he says.

Land Cover and Land Use Changes

Increasing globalisation and a changing climate are among the dominant forces that are shaping and altering island ecosystems. Their effects often manifest through changes in land cover or land use – for example, transforming natural habitats into agricultural or urban environments.

Dr Walsh and his colleagues reviewed 30 years of research and investigated the social-ecological drivers behind changes in land cover and land use on islands across the world. Satellite remote sensing allowed the team to map and examine patterns and trajectories of these changes across space and time. Projected land cover and land use change patterns for the year 2100 demonstrate that islands are disproportionately affected in comparison to mainland ecosystems.

By applying his dynamic systems model to the Island of Santa Cruz – one of four inhabited Galapagos Islands – the researchers identified the expansion of the tourism sector and economic development on the Ecuadorian mainland as the main drivers of change in land cover and land use. In 2019, 7.8% of the island's surface was degraded by direct and indirect human activities. If tourism continues to expand at the current rate, this area will double in size within just 20 years.

Although Dr Walsh and his colleagues identified a set of core processes that lead to changes in land cover and land use on islands, they found considerable variability between islands relative to their geographic location, degree of isolation, and landscape morphology. Their findings illustrate that analysis and modelling appropriate for one island's social-ecological system may not be appropriate for another.

The researchers aim to further investigate the strengths and limitations of this approach by generalising their dynamic systems model for islands, developed in the Galapagos Islands, to Hawaii and Puerto Rico as test cases. Dr Walsh suggests that developing the core model further, through the addition of components that are sensitive to particular island features, could help improve its applicability and accuracy for other island systems. 'The research moves us closer to recognising the core issues important to islands, while retaining the local context and place-based conditions that serve to mediate social-ecological relationships,' he says.

Into the Future

In addition to their interdisciplinary research, Dr Walsh and the Galapagos Initiative have developed and recruited institutions into the International Galapagos Science Consortium, created important links with the Galapagos National Park, and attracted and trained scientists and students from around the world. By cultivating strong connections and a skilled team, the Galapagos Initiative has ensured that this important work will continue well into the future – and transform the current trajectory for these precious islands, where island ecosystems are sustained by a more complete understanding of the social-ecological stressors that threaten the Galapagos Islands and other similarly challenged island setting around the globe.

Meet the researcher

Dr Stephen J. Walsh
Lyle V. Jones Distinguished Professor
Department of Geography
University of North Carolina at Chapel Hill
Chapel Hill, NC
USA

Dr Stephen J. Walsh is the Lyle V. Jones Distinguished Professor in the Department of Geography, the Director of the Center for Galapagos Studies at the University of North Carolina at Chapel Hill (UNC), and Co-Director of the UNC-USFQ Galapagos Science Center (GSC), Galapagos Archipelago of Ecuador. He co-founded the Galapagos Initiative, forming a strategic partnership with the Universidad San Francisco de Quito (USFQ), Ecuador. The initiative includes the 2011 construction of the 20,000-square-foot Galapagos Science Center on San Cristobal Island, Ecuador, a facility that hosts an extensive and intensive program of integrated and interdisciplinary science. The Galapagos Initiative emphasises research, education, and community outreach and engagement, achieved through studies conducted in the GSC labs – genetics and microbiology, marine ecology, terrestrial ecology, and spatial analysis and modelling. Through linkages forged among UNC, USFQ, GSC, and the Galapagos National Park, a DNA-pipeline was created for the genetic sequencing of collected biological samples to support a host of molecular studies of iconic, native, and introduced species in the Galapagos Islands. Other programmatic advances include the development of a Galapagos bio-bank, marine expeditions throughout the Galapagos Marine Reserve, and annual UNC Study Abroad programs for undergraduate students. In 2012, Dr Walsh launched a book series on the Galapagos Islands with Springer Nature and nine books have been published thus far in the series. In addition to informing conservation efforts for the Galapagos Islands, Dr Walsh's research is providing a global template for the study of other conflicted and challenged island ecosystems. His main research interests include human-environment interactions, coupled human-natural systems, and cutting-edge geographic methods, including remote sensing, geographic information systems, and spatial analysis.

CONTACT

E: swalsh@email.unc.edu
W: https://swalsh.web.unc.edu/

KEY COLLABORATORS

Dr Carlos F. Mena, Co-Director of GSC, Universidad San Francisco de Quito, Ecuador

SELECTED FUNDING

SJ Walsh, 2018-2020. Very high spatial resolution, commercial satellite imagery: Data applied to the study of LCLUC on Islands, NASA Land Cover/Land Use Change Program.

SJ Walsh, RE Bilsborrow, L Brewington, Y Shao, H Mattei, 2017-2020. Synthesis of drivers, patterns, and trajectories of LCLUC in island ecosystems, NASA Land Cover/Land Use Change Program.

SJ Walsh, 2015-2016. A sustainable science infrastructure in the Galapagos Islands: Design of a preliminary Galapagos data observatory, Vice Chancellor for Research, University of North Carolina at Chapel Hill.

CF Mena, SJ Walsh, RR Rindfuss, D Quiroga, G Reck, C Valle, 2013-2014. Assessing the population carrying capacity of the Galapagos Islands through spatial simulation models and scenarios of change, Galapagos National Park & World Wildlife Fund.

SJ Walsh, RR Rindfuss, D Guilkey, CF Mena, D Quiroga, 2011-2015. Modeling population-environment-interactions in a World Heritage Site: Comparison of statistical and agent-based modeling approaches to study complex systems, James S. McDonnell Foundation.

FURTHER READING

F Pizzitutti, L Brewington, SJ Walsh, Human and natural environments, Island of Santa Cruz, Galapagos: A model-based approach to link land cover/land use changes to direct and indirect socio-economic drivers of change, In Land Cover and Land Use Change on Islands 2020, Springer Nature, Cham, 183.

SJ Walsh, L Brewington, F Laso, Y Shao, RE Bilsborrow, J Arce-Nazario, H Mattei, PH Page, BG Frizzelle, F Pizzitutti, Social-ecological drivers of land cover/land use change on islands: A synthesis of the patterns and processes of change, In Land Cover and Land Use Change on Islands 2020, Springer Nature, Cham, 63.

THE UNIVERSITY *of* NORTH CAROLINA *at* CHAPEL HILL

HERBIVORE HELPERS: USING LIVESTOCK TO MANAGE RANGELANDS

Domestic herbivores – such as cattle, sheep, and goats – are remarkably important to ecosystems. Their feeding behaviours aid the management of natural habitats by preventing any individual plant species dominating the landscape. Thus, understanding livestock dietary preferences is vital for informing land management decisions. **Dr John Walker** from the Texas A&M AgriLife Research and Extension Center has devoted his career to exploring livestock dietary preferences, and how they can be manipulated to benefit rangelands. His 'Aggie Cedar Eater' (ACE) goats are now helping to control invasive juniper shrubs across the Great Plains of the US.

The Importance of Herbivory

When carnivores roamed the lands freely – and in places where they still do – herbivore populations determined the predator population size. In turn, predators kept the number of herbivores down, and thereby prevented overgrazing.

The disruption of this delicate balance – through the loss or exclusion of wild herbivores and predators from many areas – has had consequences for ecosystem function that scientists are only beginning to understand. For example, in the absence of sufficient fire and browsing herbivores, grasslands are susceptible to being taken over by woody plant species. However, human activities can also help to maintain or restore ecosystem function.

Grazing livestock can replace the ecological role of wild herbivores in managing vegetation and maintaining the landscape. In the US, herbivory on 'rangelands' – grasslands, shrublands, woodlands, deserts, and wetlands grazed by livestock – is vital to maintaining these landscapes. However, over-grazing can also lead to the loss of individual plant species.

Just like humans, animals have dietary preferences. It is well recognised that livestock grazing affects the composition of rangeland plant communities. By selectively feeding on particularly palatable plants, livestock give unpalatable plant species the opportunity to outcompete the grazed species.

For decades, researchers have been exploring how to manage grazing on rangelands effectively, both to increase livestock productivity and to improve environmental outcomes. A key aim is to target the effects of selective feeding on rangeland habitats. Dr John Walker, a rangeland expert and Professor at Texas A&M AgriLife Research and Extension Center in Texas, has spent more than three decades investigating dietary preferences in livestock, and how they can be influenced to achieve management goals. His overarching goal has been to improve livestock productivity while enhancing the role of

livestock grazing to improve rangeland health.

Through some innovative thinking and dedication, Dr Walker has successfully demonstrated how selective breeding can be used to develop livestock that have dietary preferences for specific plants. His 'ACE goats' are helping to control the invasive juniper shrub on grasslands across Texas and the surrounding states.

In the US, juniper is a shrub that grows quickly, spreads fast, and outcompetes native plants. It is especially damaging to grassland ecosystems, where it routinely replaces grass species and changes the landscape. By 2013, there were 50 million acres of juniper in Texas alone – an area larger than the entire state of Nebraska – and the plant has been recorded in all 50 states.

Currently, Dr Walker is contributing his considerable expertise – and his juniper-loving goats – to a new collaborative project between rangeland scientists across multiple states, investigating how controlled fires and herbivory can be used to effectively manage rangelands. 'Effective use of any type of biological control requires an understanding of the grazing behaviour of herbivores and the ecology of the target plant species,' Dr Walker explains.

Investigating Dietary Preferences

Determining the dietary preferences of livestock is tricky. After all, you can't ask a cow what they like to eat. Understanding what livestock have been eating, which plants they prefer, and how their feeding behaviours can be influenced are fundamental first steps for developing techniques that support effective rangeland management.

Some methods for determining diet selection are more effective than others. Analysing collected faecal samples is simple, repeatable, inexpensive and useful for both wild and domestic animals. The advanced technologies available to analyse faecal composition each has its own limitations.

They also developed a technique to calibrate and validate a method for determining faecal plant components. The method, called 'near-infrared spectroscopy', uses light to accurately assess the botanical composition of samples. The results demonstrated that the method is most accurate when calibrated with samples from the same conditions, for example, a single group of sheep grazing in the same field at the same time. The digestibility of consumed plants and the interactions between dietary components during digestion complicate the task of maintaining the same condition. However, for the right research projects, near-infrared spectroscopy can be a valuable tool.

Manipulating Livestock Dietary Preferences

In some of his earliest research, Dr Walker investigated whether selective feeding could be controlled by managing grazing patterns. Confining and moving livestock between smaller sections of land gives plants the opportunity to recover between grazing. This allows higher stocking densities to be maintained, increases livestock productivity, and has numerous ecological benefits. However, Dr Walker and his colleagues discovered that animals do not become less selective when you control where they graze. For example, sheep will avoid eating leafy spurge even when they are running out of other food plants.

Undeterred, Dr Walker turned his attention to the root causes of dietary preferences. His epiphany came in the form of a blue heeler dog called Gaucho. 'One day I happened to read an article that described how to teach a heeler to head cattle, which I thought would be a very useful ability. So, I trained Gaucho to do an outrun as good as any border collie,' explains Dr Walker. 'Unfortunately, when I tried to use this new skill on cattle, Gaucho reverted to instincts, forgot everything he had learned and heeled the beast.'

'The difference among different dog breeds demonstrates that animals can be selectively bred to modify their foraging behaviour,' he continues. 'This led me to ponder the question: if we could modify the behaviour of dogs through selective breeding, why couldn't we do the same for livestock?'

Dr Walker and his colleagues knew that cattle, sheep and goats have different dietary preferences, and they demonstrated that it is the post-ingestion results that causes these differences. In other words, if eating a plant gives an animal a stomach ache, they won't eat want to eat it again.

Initially, the researchers identified the feeding behaviours of the goats using his near-infrared spectroscopy technique. To test his theory, the research team began selectively breeding goats with the aim of either increasing or decreasing their preference for juniper. This allowed the researchers to determine physiological differences in high and low juniper consuming goats.

The resulting goat breed – the 'ACE goats' – love to eat juniper. Dr Walker's findings demonstrated that in just eight years of breeding efforts, the ACE goats were able to consume 50% more juniper than their original breed. These ACE goats also showed a much better ability to digest the unpalatable compounds in juniper that give it its distinctive odour.

The Curious Pairing of Goats and Fire

Dr Walker's super-goats are now helping scientists investigate how to improve rangeland management. In their new five-year project, entitled 'Enhancing Livestock Production from Rangelands in the Great Plains,' experts from multiple institutions have teamed up with landholders to develop techniques to control juniper, prevent wildfires, and increase livestock production by 20% to improve rural community resilience.

Wildfires used to be fairly uncommon on the Great Plains, but have increased alarmingly in the last 50 years. Since 2002, Texas and Oklahoma have been in the top six states most impacted by wildfires. In 2017, Texas achieved the unenviable position of having the greatest number of wildfires and the largest acreage burnt. While climate change related extreme weather is doubtlessly playing a role in this increase, Dr Walker suggests that changes in land management practices are also contributing.

'In 1965, there were 4.6 million goats in the Texas Hill Country, and juniper encroachment and wildfires were not a problem,' he says, 'Today there are less than 1 million goats in Texas, and both juniper encroachment and wildfires are a concern.'

The researchers suggest that prescribed, controlled fires are the only viable way to maintain good forage quality and quantity on grasslands. But the encroachment of juniper onto grasslands complicates this process. Juniper outcompetes grass species, reducing both grass productivity and spatial continuity. With less grass to burn, the intensity of fires is reduced. And reduced intensity helps juniper survive the fires.

ACE goats can help to solve this problem, in a controlled fire and grazing regime called 'pyric herbivory'. The goats in conjunction with prescribed fire prevent juniper from re-establishing and thus maintain grasslands and protect them from future juniper encroachment. Because goats prefer to forage in recently burnt patches with new regrowth, the effects of pyric herbivory can be localised.

Plant regrowth in burnt patches also have a higher protein content and are easily digestible, reducing the need for protein supplements to support livestock. The higher productivity achieved with pyric herbivory improving economic returns, thus improving the resilience of rural communities that depend on livestock production.

In addition to developing pyric herbivory techniques to manage rangelands, the researchers are establishing Demonstration Ranches to ensure this knowledge is disseminated to producers, resource managers, agribusiness leaders, and the public. With their educational programs, the team aims to overcome the social barriers to the use of prescribed fire and livestock grazing.

Meet the researcher

Dr John W. Walker
AgriLife Research and Extension Center
Texas A&M University
San Angelo, TX
USA

Dr John W. Walker began his research career investigating dietary preferences in livestock for his doctoral studies at Texas A&M University. He currently holds the position of Professor at the Texas A&M AgriLife Research & Extension Center, where he conducts research on increasing the efficiency and sustainability of range livestock and wildlife production. His research interests relate to the development of new technologies for modifying diet selection in grazing ruminants, through selective breeding, nutritional interventions, and learning. Dr Walker used his knowledge of livestock foraging behaviour with an understanding of plant ecology to develop the concept of targeted grazing. Targeted Grazing is the carefully controlled grazing of livestock to accomplish specific vegetation management objectives. To improve targeted grazing prescriptions he developed calibrations for near-infrared spectroscopy to predict the botanical composition of livestock diets using faecal samples. He is currently developing image analysis procedures for micro-histological analysis of faeces to determine the botanical composition of herbivore diets for a wide variety of species. In addition to his research activities, Dr Walker also oversees the management of around 20,000 acres of rangeland across six properties in four counties.

CONTACT

E: jwalker@ag.tamu.edu
W: https://sanangelo.tamu.edu/people/research/jw/

KEY COLLABORATORS

Dr Bradford P. Wilcox & Dr Ben Wu, Texas A&M AgriLife Research
Dr Sam Fuhlendorf & Dr Laura Goodman, Oklahoma State University
Dr Dirac Twidwell, University of Nebraska

FUNDING

USDA-National Institute of Food and Agriculture

FURTHER READING

S Garnick, PS Barboza, JW Walker, Assessment of animal-based methods used for estimating and monitoring rangeland herbivore diet composition, Rangeland Ecology & Management, 2018, 71, 449.

JW Walker, Creating a 'Super Juniper Eating Goat', Ranch and Rural Living, 2013, 95, 20.

K Launchbaugh, J Walker and R Daines, Targeted Grazing - a natural approach to vegetation management and landscape enhancement, American Sheep Industry Association, Centennial, CO, 2006.

JW Walker, SD McCoy, KL Launchbaugh, MJ Fraker, J Powell, Calibrating fecal NIRS equations for predicting botanical composition of diets, Rangeland Ecology & Management/Journal of Range Management Archives, 2002, 55, 374.

G Snowder, JW Walker, KL Launchbaugh, LD Van Vleck, Genetic and phenotypic parameters for dietary selection of mountain big sagebrush (Artemisia tridentata Nutt. ssp. vaseyana [Rydb] Beetle) in Rambouillet sheep, Journal of Animal Science, 2001, 79, 486.

JW Walker, Grazing management and research now and in the next millennium, Rangeland Ecology & Management/Journal of Range Management Archives, 1995, 48, 350.

JW Walker, RK Heitschmidt, SL Dowhower, Some effects of a rotational grazing treatment on cattle preference for plant communities, Rangeland Ecology & Management/Journal of Range Management Archives, 1989, 42, 143.

JW Walker, RK Heitschmidt, EA de Moraes, MM Kothmann, SL Dowhower, Quality and botanical composition of cattle diets under rotational and continuous grazing treatments, Rangeland Ecology & Management/Journal of Range Management Archives, 1989, 42, 239.

TEXAS A&M AGRILIFE RESEARCH

PLANTING HEDGEROWS TO BOOST BIODIVERSITY AND PROTECT CROPS

From a bird's eye view, farmlands are conspicuous. Unlike wildlands, swaths of agricultural fields form neat squares, fitting together in a landscape-sized jigsaw puzzle. The edges of the puzzle pieces stand out most: dark emerald lines contrasting against the light green interior crisscross across the land. These narrow, vegetated strips – or hedgerows – have been planted for centuries but are receiving renewed interest. Often referred to as 'living fences', hedgerows are buzzing communities that provide various ecosystem services. **Laura Arneson Horn**, the owner of Wild Bee Project in Salt Lake City, works to establish hedgerows and promote their positive impacts on native pollinators and other beneficial insects.

Ecosystem Services of Hedgerows

Hedgerows have been planted in Europe for hundreds of years to enclose animals and define farm boundaries. The narrow strips of woodland habitat are planted with woody trees and shrub species interspersed with herbaceous plants.

Although hedgerows were initially planted to delineate ownership boundaries and provide livestock boundaries and shelter, these edge habitats have been more recently recognised as essential ecosystems.

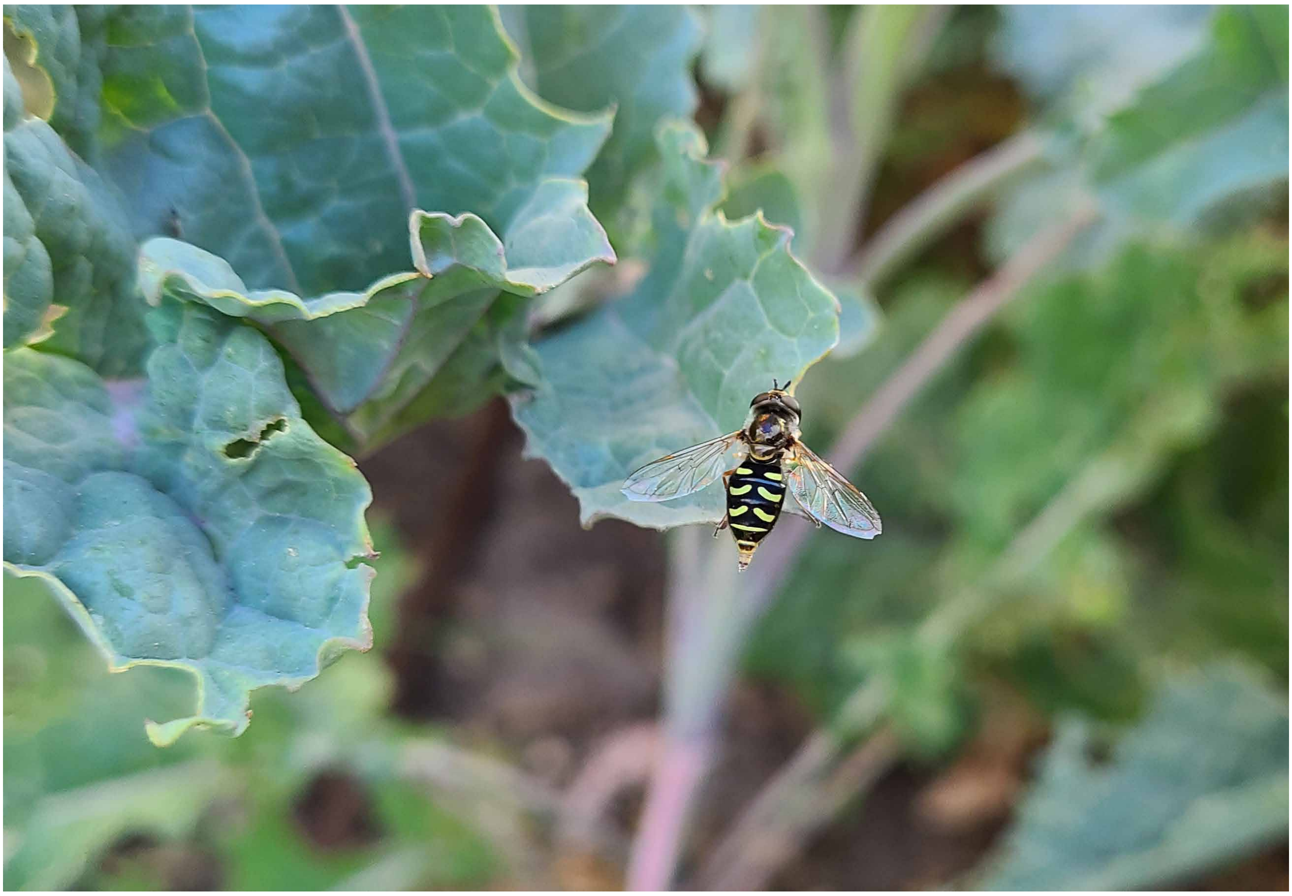
Hedgerows harbour tremendous biodiversity in a landscape often dominated by monoculture and managed lands. This is partly due to their intentional design – the interior woody, shaded habitat attracts forest-adapted animals and plants. At the same time, the outer, sunnier, herbaceous layer provides a niche for grassland species. Hedgerows have been shown to provide habitat for hundreds of plants, insects, mammals and fungi that would otherwise be driven out of inhospitable farmland areas. All this activity translates below-ground to increased soil diversity.

Beyond creating a biodiversity sink, hedgerows are well-known for connecting isolated, fragmented farms. They give refuge to species who either live near the farms or travel through.

By providing these ecosystem services, hedgerows indirectly work for the farmer. The diverse plant life in a hedgerow attracts pollinators such as wild bees, which also pollinate crops on nearby farms and improve farmers' yields. Bats, birds, and other insects are also drawn to hedgerows, where they predate on insect pests, reducing the need for farmers to manage pests by spraying chemical insecticides, which that can have devastating effects on the local environment.

Finally, these small slices of woodland can be substantial carbon sinks, helping to offset the greenhouse gas emissions associated with agriculture.

Because of their numerous benefits, planting diverse hedgerows on every farm seems like a no-brainer. To some extent, planting hedgerows in farm areas that did not traditionally have them – such as fields in central California – is becoming more common. However, hedgerows are not cheap and require significant maintenance,



including regular trimming and planting. Beyond the cost, some farmers fear that hedgerows might also attract unwanted animals, such as starlings, which may feed on the crop themselves.

Laura Horn, a conservationist in Salt Lake City and owner of the Wild Bee Project, understands both the benefits of hedgerows and the hesitancy of farmers. That is why she is working to help farmers plan, install, and maintain hedgerows. Beyond managing the nuts and bolts of hedgerow planting, she prioritises education, ensuring that the farmers perceive hedgerows as beneficial, motivating them to continue expanding hedgerows on their own.

Conservation Biological Control

Much of Horn's work at the Wild Bee Project focuses on 'conservation biological control', colloquially referred to as 'farmscaping', the practice of planting habitat on a farm to support pollinators and other beneficial insects that attack crop pests. In Horn's work, this habitat often takes the form of hedgerows.

In 2018, she started to investigate whether hedgerows could help to control the cabbage aphid. With more farmers in the region growing kale and brassica crops year-round to satisfy customer demand, cabbage aphid problems have increased. The cabbage aphid has a host of numerous natural enemies, making them an ideal candidate for a farmscape study.

To help Utah producers prevent more losses, Horn sought collaborations with farmers in the Salt Lake City area to investigate whether hedgerows could encourage beneficial insects to predate on cabbage aphids. In partnership with other local contractors, she aimed to establish aphid-control hedgerows at six farms and evaluate their potential to attract natural enemies of cabbage aphids.

Horn and her colleagues took a scientific approach: the team planted control plots at varying distances from hedgerows. This way, they could compare the control plots and established plots to evaluate whether hedgerows can reduce aphid damage to kale crops.

As usual, Horn also emphasised education. She designed three hedgerows to serve as demonstration sites to educate other local urban farmers. Throughout the project, the team also conducted cost-benefit analyses, to identify ways to lower the barrier to adopting conservation control practices such as planting hedgerows.

She visited six different sites and worked with the staff to identify the best hedgerow locations, and discussed the unique goals each farmer was hoping to address with a hedgerow. The project demanded creativity, as many of the farms were small and in urban areas, without large areas to dedicate to planting hedgerows.

By the end of the study's first year, Horn and her team successfully established six hedgerows at six different sites, with three of them acting as demonstration sites.

Hedgerow Planting 101

In the naturally arid and urban area surrounding Salt Lake City, Horn worked with farmers to select the most appropriate native species for their hedgerows, customising each one to the farm's goals, space, and resources.

Horn planted hedgerows adjacent to the greenhouse in one site, designing it to capture water runoff. The drought-tolerant mix of grasses, shrubs, and flowering perennials require very little maintenance, provide continuous food and shelter for beneficial insects and other wildlife, and are a source of herbs for the farm.

In another nearby farm, she planted a hedgerow adjacent to the growing area near an access road and irrigation ditch. At this site, the width of the hedgerow was severely limited, so the team planted columnar shrubs and bunchgrasses that could fit the narrow space and provide a windbreak and barrier to pest seeds that were carried by the wind.

Farmers at a historic farmhouse yard needed a hedgerow to serve one of its original functions – as a 'living fence' to enclose the garden. Horn worked with the farmers to pick modern cultivars of traditional shrubs, which aesthetically matched the historic farmhouse and provided a 'historic' hedgerow.

Collecting Data

In the two years following hedgerow planting, Horn and her team assessed the abundance of beneficial insects such as ladybugs, hoverflies and wasps on kale crops at four of the six study sites. The team also measured aphid infestation by counting the number of aphids per plant and surveying farmers to get an idea of aphid infestation levels pre-hedgerow planting.

Using this data, the researchers investigated whether kale planted closer to a hedgerow would experience less damage from cabbage aphids. In some farms, anecdotal evidence has suggested that kale planted directly adjacent to a hedgerow experiences less severe aphid infestation than kale planted 15 metres away from a hedgerow. However, this was not the case at all the farms; in some situations, kale planted adjacent to hedgerows had similar levels of infestation as kale planted almost 30 metres from a hedgerow.

Many of Horn's observations have provided valuable insights into how best to install hedgerows in northern Utah. For example, Horn and her colleagues intentionally incorporated flowering perennials into the hedgerows to see if they would attract beneficial insects more than annuals.

'I found after a couple growing seasons that cool-season perennial grasses were the most practical foundation for a hedgerow in this arid region,' says Horn. 'Having a base row of grasses allows farmers to double their hedgerow area after two years by dividing plants, which is not true for shrubs or even most perennial flowering plants.'

She noted that the seeded annual flowers, such as cilantro and buckwheat, are more effective for attracting hoverflies, whose larvae predate on the cabbage aphid. These small hoverflies were found through mid-summer on most farms surveyed. While annual plants may directly provide the resources needed by beneficial insects, including pollen and nectar, perennials probably offer better shelter and wind protection, critical for hoverflies to move between plants.

The team's work is an important first step in cultivating and sustaining farmers' interest in hedgerows. 'Most farmers I worked with are able to maintain and expand their plantings over time as they saw fit, after receiving assistance with the initial plan and installation through my project,' Horn explains.

With more urban farmers in the region installing hedgerows, Horn and others will have more long-term data that may offer increased insight into the specific benefits hedgerows can provide in controlling crop pests.

Outreach

As part of the project, Horn gave multiple tours of the demonstration sites, workshops, and talks. One of the farms plans to double their hedgerows, while others lauded the benefits of their hedgerows. Horn continues to publish in extension newsletters targeted at farmers, where she describes the benefits of hedgerows and which plants work best on different farms.

Although the project did not show any scientific link between hedgerows and a reduction in cabbage aphid infestation, it succeeded greatly in forging new relationships and connections between urban farmers in Salt Lake City. Most importantly, many farmers now view a perceived economic benefit from the hedgerows, with many reporting that they will continue to expand their hedgerows into the future.

Meet the researcher

Laura Arneson Horn
Wild Bee Project
Salt Lake City, UT
USA

Laura Arneson Horn is a conservationist and owner of the Wild Bee Project, an organisation dedicated to helping vegetable farmers attract beneficial insects and increasing awareness of native wild bees. After receiving her MS in Biology from Utah State University in 2004, Horn spent a decade as an environmental specialist for a consulting firm in Utah. An avid bee-lover, she noticed a need for specialists who could consult with farmers to help attract native pollinators and beneficial insects. She started the Wild Bee Project in 2015 to address this need. Her work at the Wild Bee Project is broad, with outreach projects running alongside scientific studies primarily funded by federal grants. Horn has spearheaded projects to help farmers plan and execute natural pest control strategies, mainly through planting on-farm hedgerows. Horn also conducts talks and workshops to spread her love of the wild bees of northern Utah to farmers and enthusiasts alike.

CONTACT

E: wildbeeproject@gmail.com
IG: @wildbeeproject
W: http://www.wildbeeproject.com/

KEY COLLABORATORS

James Loomis, Green Phoenix Farm and Wasatch Community Gardens, Salt Lake City, UT
Kristin Kropp, Backyard Urban Garden Farms, Salt Lake City, UT
John Borski, Borski Farm, Kaysville, UT
Luke Petersen, Petersen Family Farm, Riverton, UT

FUNDING

Sustainable Agriculture Research and Education (SARE) program

FURTHER READING

LA Horn, Supporting Natural Enemies of the Cabbage Aphid with Hedgerow Plantings, Final Report for Grant OW18-007, Sustainable Agriculture Research and Education (SARE) 2021.

L Horn, Conservation Biological Control in Utah, Utah Pests Quarterly Newsletter, 2020, 14, 3-4.

CULTIVATING SUSTAINABLE URBAN LANDSCAPES WITH NATIVE PLANTS

Landscapes exist on a spectrum – from those with minimal human impact, to urban sites wherein most natural features have been destroyed. As disturbed urban sites become more geographically prominent, imperatives to create managed urban habitats that provide societal and environmental services are increasingly urgent. Using native plants is a core principle of sustainable urban design, yet we lack standardised protocols to produce enough native plant products to meet demand. **Dr Stephen Love** at the University of Idaho has employed his expertise in plant breeding to develop high-throughput native plant domestication processes, to enhance offerings of native plants to people who wish to transform personal and public spaces into attractive, resilient ecosystems.

Urban Ecology

Preserving the Earth's remaining wilderness areas will not be enough to tackle global climate change and ecological collapse. Instead, we must integrate ecological resilience into areas where humans and wildlife coexist. By recognising that humans are part of the natural landscape rather than separate from it, we can jointly address the needs of wildlife, ecosystems and humans with intelligent, sustainable design.

With a growing global interest in the intersection between wild and urban spaces, more organisations and individuals are searching for ways to improve the ecological resilience of private and public spaces. However, many public areas and gardens are intensively managed, displace native habitats, and require unsustainable amounts of irrigation, fertiliser and pesticides.

Native plants play a crucial role in urban and agricultural ecological restoration. For example, many farmers plant tree hedges as windbreaks, which also provide native habitat for birds and mammals that naturally prey upon common agricultural pests.

Indeed, many different restoration efforts revolve around native plants. Without them, native wildlife health decreases, and essential ecosystem services, such as water purification and soil regeneration, weaken.

However, with an eye toward aesthetics over sustainability, many public areas are dominated by non-native, ornamental species. The cultivation of non-native plants in areas that are quite different from the habitats in which these species evolved requires intensive management to mimic the plants' ideal growing conditions. On the other hand, plants that are endemic to a region already have adaptations to survive and thrive within that particular environment.

However, native plant production has not traditionally been lucrative. Unlike the case for ornamental species, we do not have processes in place to cultivate enough viable native plant products for revitalising urban areas. To meet demand, we must create new, exciting, and attractive native plant products, make them easily available to consumers, and create efficacious propagation protocols so the plants provide an economically viable option for nurseries.

Dr Stephen Love of the University of Idaho Aberdeen Research and Extension Center recognised that consumers in arid climates of the western US are interested in creating sustainable urban spaces, but they lack access to a palette of native plants of sufficient variety, quality, and quantity to make it practical.

In 2005, he began a native plant domestication program to meet regional consumer needs. His team created a stepwise approach for collecting, evaluating and domesticating native plants, while maintaining their habitat-supportive characteristics. Their approach also involved developing propagation protocols that nurseries could easily adopt. The idea was to create a large palette of nursery products that are attractive to the consumer while also being suitable for nursery production.

'This domestication project is unique in design and operation with respect to its potential for producing large numbers of new native plant products that retain the ability to provide ecological services,' says Dr Love. 'The adopted approach is proving effective in providing large numbers of native species with potential to transform global urban horticultural practices and make native plant products competitive alternatives to exotic options currently available.'

The ecological benefits of this project are numerous. 'Issues such as reducing the use of potentially invasive exotic species, developing diversity in urban landscapes, creating urban habitat for small animals, and supporting pollinators, can all be addressed with native plants,' explains Dr Love.

Sourcing Native Seed

To begin his native plant domestication project, Dr Love needed seeds and cuttings from plants with ornamental potential. First, he identified specific groups of species that had characteristics that would allow them to perform well in urban landscapes in the Intermountain West region of the USA. In an extensive collection campaign, his team conducted forays as far north as the Canadian border, south to northern Arizona and New Mexico, east to the edge of the Great Plains, and west to the coastal ranges of Washington, Oregon, and California.

So far, Dr Love and his dedicated team of researchers have made over 4,000 collections of seeds and cuttings, and are planning more forays to new areas in Idaho and surrounding states. In August 2022, they plan a foray into the Chiricahua mountains of Arizona, and in June 2023, they hope to collect material from the Bighorn Mountains in Wyoming.

In addition to their own collection efforts, Dr Love's team has found other sources of research material. 'Over the years, we have worked to find other sources of starting material, such as professional collectors, native plant societies, interested colleagues, and the random person with interest in the project that drops off the occasional seed envelope,' he says. As a result of their efforts, the team has acquired seeds from over 1,500 species that are native to the United States Intermountain West.

Evaluate, Refine, and Propagate

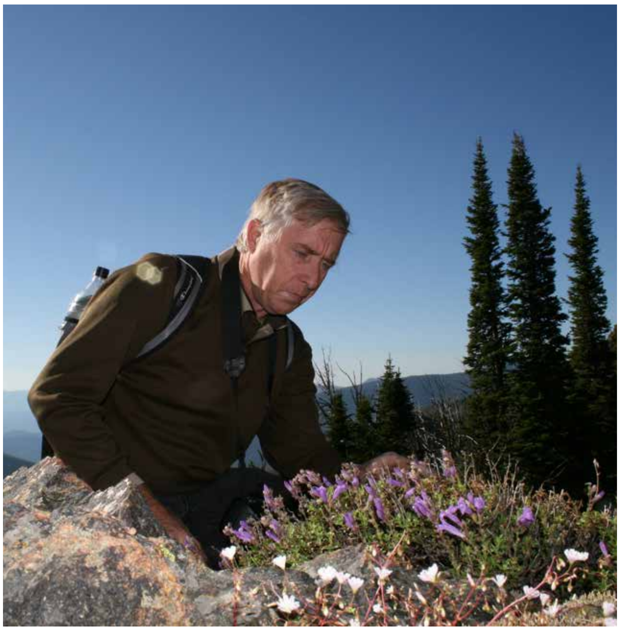
Wild populations of a given plant species can often comprise diverse individuals with unique appearances and qualities. As such, growing wild seeds can lead to variability that is not acceptable to the consumer. Additionally, plants taken from native habitats have characteristics that most gardeners may find frustrating to manage, such as limited flowering times and adaptation to a narrow set of growing conditions.

Thus, an essential part of Dr Love's strategy was to evaluate each native species that his team collected to determine its capacity to satisfy the consumer's preference for beauty and predicable performance, while also ensuring that it can withstand typical nursery handling procedures. To this end, they created a three-acre evaluation plot at the Aberdeen Research and Extension Center. Here, the researchers carefully monitor the horticultural quality and propagation efficiency of each 'accession' – a term referring to a group of seeds or cuttings from the same species collected from a single location on the same date.

To do so, Dr Love and his colleagues evaluate the tolerance of each accession, in terms of nursery handling procedures, winter cold, and garden pests. They also assess horticultural traits such as growth rate, bloom potential, bloom timing, flower colour, resistance to problems created by high pH soils, overall aesthetic value, and other characteristics. These assessments allow the research team to remove any inferior plants that cannot handle high volume propagation procedures or do not have the aesthetic qualities that most gardeners desire.

Any plants from an accession that pass the first phase of the evaluation process are moved through a progressive cycle intended to partially domesticate the species without hybridisation, and develop high-value, uniform plant lines. The number of selection cycles is dictated by the plant's performance in the previous cycle and may be repeated through four to five generations. Afterwards, the researchers move the improved plant lines into 'increase blocks', where the plants are grown until transferred to an industry partner.

This simple, systematic, cyclical approach allows for assessments to be completed on hundreds of native species simultaneously – as opposed to more common research protocols that



result in intensive research on one or a few species. The team's approach has resulted in the development an extensive palette of native plants that are attractive to consumers, provide ecosystem services and are easy to mass-produce.

'To date, we have released over 100 domesticated native plant products to the nursery industry, and about 60 of those products are currently being produced commercially,' says Dr Love. 'And the pipeline is full, meaning a continuous supply of native plant products will be released and marketed in the next few years. The long-term potential is incredible.'

As part of this product development process, Dr Love's team has conducted research to develop or improve propagation protocols for many native species, most of which have never been exposed to standard nursery practices. For example, they have published several papers on improved techniques for enhancing the germination rates of seed-propagated plants.

One example is *Castilleja*, commonly known as Indian Paintbrush. An emblematic wildflower of the western US, *Castilleja* is beloved but is very difficult to propagate. This is because it is a partially parasitic plant, and so must be grown with a host to perform well. In a 2017 paper, the researchers provided key propagation protocols focusing on planting *Castilleja* with suitable companion species. The team has also performed research to determine the optimal conditions and procedures for plants propagated by cuttings.

Finding Industry Partners

A critical yet underappreciated aspect of applied research is to find the right industry partner to connect applied science with public interest and usage. In this case, the University of Idaho signed a partnership agreement with Conservation Seeding and Restoration to create Native Roots, LLC, a nursery in Twin Falls, Idaho.

Native Roots, LLC has first right of refusal to all native plant products developed by the University of Idaho native plant domestication project. They have built up stocks of plants to provide commercial scale seed increase and vegetative cutting blocks, greenhouses, handling and growing equipment, and storage facilities at their site in Filer, Idaho. They also market and ship both wholesale and retail products from the nursery. As a result, Dr Love, in partnership with Native Roots, LLC will have a direct and lasting impact on the competitiveness and profitability of Idaho's native plant production industry. Now, consumers who want to cultivate native plants will have diverse options.

Successes So Far

Through their research, standardised domestication procedures, and industry partnerships, Dr Love's team is making it easy for ecologically-minded consumers in Idaho and throughout Intermountain West to purchase and plant native species that will thrive in their gardens. The team's systematic process of acquiring, evaluating, selecting, and releasing native plant products to the Idaho nursery industry has made it easier for consumers to transform their landscapes into diverse, beautiful and sustainable habitats. The project has already reduced the cultivation of exotic plants, increased diversity in urban landscapes, reduced water consumption, created habitat for native wildlife, and supported threatened pollinators.

With more plant species expected to be released in the coming years, Dr Love and his team have transformed the native plant industry in the Intermountain West region. Perhaps even more importantly, the methodological processes they have developed can be used in any region in the world, towards the creation of sustainable, ecologically-rich landscapes.

Meet the researcher

Dr Stephen L. Love

Aberdeen Research and Extension Center

University of Idaho

Aberdeen, ID

USA

Dr Stephen Love has three decades of experience in applied plant science research. After earning his PhD in Horticulture and Plant Physiology at Clemson University in South Carolina, Dr Love moved to the University of Idaho, where he is now an Extension Professor of Horticulture. Since 2005, he has served as the State-Wide Urban Horticulture Specialist, providing leadership to a Horticulture and Small Farms Team in which he trains team members and facilitates development of public education programs on topics related to water conservation, landscape management, and gardening. Associated with these educational activities, Dr Love created and directs a research program designed to domesticate native plants with goal to conserve water, create biologically diverse urban habitats, and provide support for threatened pollinators. The native plant domestication program is conducted at the University of Idaho's Aberdeen Research and Extension Center. Dr Love bridges applied research, industry marketing, and public education to provide native plant products to ecologically minded consumers.

CONTACT

E: slove@uidaho.edu

W: https://www.uidaho.edu/cals/plant-sciences/our-people/stephen-love

KEY COLLABORATORS

United States Department of Agriculture-United States Forest Service

United States Department of Interior-Bureau of Land Management

Ben and Katie Pierce – technical assistants for the native plant project

Steven Paulsen – owner and operator of Native Roots, LLC

FUNDING

Idaho Nursery and Landscape Association

United States Department of Agriculture-Agricultural Marketing Service

United States Department of Agriculture, Western Education and Research Activity (WERA-1013)

FURTHER READING

A Paudel, Y Sun, LA Rupp, JG Carman, SL Love, Vegetative propagation of *Ceanothus velutinus* using stem cuttings, Native Plants, 2022, 23, 123-129.

SL Love, T Salaiz, WJ Price, Selectable variation for essential turfgrass quality traits among and within Idaho fescue (*Festuca idahoensis*) accessions, Native Plants, 2021, 22, 13-29.

LA Rupp, RM Anderson, J Klett, SL Love, J Goodspeed, J Gunnell, Native and Adapted Plant Introduction for Low-water Landscaping, HortTechnology, 2018, 28, 431-435.

AA Alosaimi, RR Tripepi, SL Love, Micropropagation of *Epilobium canum garretti* (Firechalice) by axillary shoot culture, HortScience, 2018, 53.

SL Love, TA McCammon, Compatible host/parasite pairs enhance propagation of paintbrush (*Castilleja* spp.), Native Plants, 2017, 18, 253-265.

SL Love, R Tripepi, T Salaiz, Influence of harvest timing and storage interval on rabbitbrush seed germination, emergence, and viability, Native Plants, 2014, 15, 98-108.

University *of* Idaho Extension

SUSTAINABLE FOOD SECURITY

THE EUROPEAN SOCIETY OF AGRICULTURAL ENGINEERS

Founded in 1992, the European Society of Agricultural Engineers (EurAgEng) promotes the profession of Agricultural and Biosystems Engineering and the people who serve it. In this exclusive interview, EurAgEng's President, Professor Fátima Baptista, discusses how the Society supports scientists and engineers in the multi-disciplinary field of Agricultural and Biosystems Engineering, facilitates knowledge exchange and promotes collaboration, towards improving food security and agricultural sustainability.

To begin, please tell us a little bit about the history of EurAgEng.

The European Society of Agricultural Engineers (EurAgEng) was established in 1992 in a spirit of collaboration, to bring together specialists who recognised the need to communicate knowledge and experience, to foster mutual understanding and to promote professionalism among National Societies of agricultural engineers in Europe, as well as among individuals.

The successful series of agricultural engineering conferences demonstrated the strong desire for mutual contact and exchange among agricultural engineers throughout Europe, who were seeking to meet the challenge of increasing the food supplies and to resolve the diverse demands on the agricultural sector in industrialised nations.

What exactly are the fields of Agricultural Engineering and Biosystems Engineering?

Traditionally, Agricultural Engineering was focused on technologies applied to agricultural sciences including vegetable crops, animal production and forestry. The main topics of research and technological development were mechanisation, irrigation, rural buildings and soil management.

Biosystems Engineering is an updated version, with a broader application, dealing with the technologies for food, feed, biomass, fibre and energy, with respect for nature, the environment, the landscape and rural communities.

In fact, we prefer to use the term 'Agricultural and Biosystems Engineering', which includes all the research and technology developments, and deals not only with the technology itself but also with economic and environmental impacts. This implies a multi-disciplinary and trans-disciplinary work to enhance sustainable production systems. A key goal is to improve the efficacy and sustainability of agricultural practices.

Nowadays, research projects have a multi- and interdisciplinary nature, involving several scientific areas and partners coming from different sectors: scientific and academic, farmers, engineers, distribution specialists, consumers, public institutions, and so on. Agricultural engineers are key in projects to develop innovative technologies and solutions to promote a sustainable agricultural production.

How does EurAgEng support the Agricultural and Biosystems Engineering community and accelerate research in this field?

EurAgEng's mission is to support scientists and engineers working on multi and trans-disciplinary projects in the field of Agricultural and Biosystems Engineering, to coordinate the exchange of scientific and engineering achievements, adapt education programs to the needs of the sector, and to promote the collaboration between academic and industry research.

To achieve this, EurAgEng helps to organise the bi-annual AgEng conferences. The last conference was in July 2021, which was online due to the pandemic, and was organised by the University of Évora, Portugal.

AgEng conferences are an opportunity to bring together engineers, academics, researchers and technicians to exchange knowledge and ideas, to present innovations and to discuss the state-of-the-art and future perspectives for agricultural engineering. The conference provides the opportunity, especially for young engineers, to present their work and make contact with other experts. The next AgEng conference will be in Berlin between November 22nd and 23rd.

Every other year there is as a prequel to the AGRITECHNICA show and the Land.technik conferences, which are linked to EurAgEng. These conferences are more oriented towards industry researchers with bigger focus on technology than on agricultural practices.

EurAgEng also sponsors the AgriTECH days conference as a prequel for the Paris agricultural machinery show SIMA, as organised by AXEMA, the French association for the agricultural machinery industry.

EurAgEng brings together agricultural and biosystems professionals from the national societies of agricultural engineers in Europe and constitutes a platform to enhance communication and the transfer of knowledge and experience. Promoting the connection between professionals plays an important role in enhancing research projects and collaboration, involving professionals from academia, technicians, farmers and other stakeholders.

The EurAgEng Official Scientific Journal, *Biosystems Engineering*, is also an example how EurAgEng supports agricultural and biosystems professionals. Another example is the EurAgEng Awards, which recognise outstanding professionals.

Tell us about your focus on sustainable agriculture – both in terms of environmental sustainability and ensuring global food security into the future.

First of all, I need to say that there isn't agriculture production with zero impacts. That is not possible. It always has some interference. Also, when we refer to sustainable agriculture it is important to emphasise that this means environmental, economic and social sustainability.

It is very important that agricultural production limits impacts to its surroundings. Sustainable agriculture means respecting and minimising impacts on biodiversity, maintaining soil and water health, respecting the use of water and other resources. It also implies resilience to the consequences of climate change.

There will always be different interests and challenges that require trade-offs. Ensuring global food security is a huge challenge concerning not only production but also logistics and processing, and the inevitable cultural and political implications. However, sustainable agriculture and food security are two faces of the same coin. Only with sustainable agriculture can food security be kept intact.

In what ways will the Russian invasion of Ukraine impact Europe's food supply? What can we do to adapt our agricultural systems to ensure food security?

The pandemic situation brought us into an unusual and unexpected situation, that changed our lives, and showed the importance of health systems, science, technology and food supply systems. Regardless of the lockdowns, these sectors had to keep performing. Farmers continued to work the land and make us realise how import the sector is to feed the population, ensure food security, and to prevent chaos and war.

But war hit us in any case, and it is impacting food supplies, creating scarcities of certain products and resulting in rising food prices globally. This is not only due to the blockage of grain exports but also blockages of crucial fuel, fertilisers and even parts for machinery. Food scarcities are expected to increase further, which will mainly affect the poorer regions of the world with higher budgets spent on food and less negotiation power to get access to food, pesticides and fertilisers.

European farmers are feeling the cost of fuel, fertilisers and pesticides, but that is nothing new. Overall, European agriculture was in crisis long before now, with farmers operating on very small margins and being trapped between the demands of food security and the growing pressure to become more sustainable. But cheap prices lead to quantity production not quality production. With the very high prices for agricultural products, farmers may get more interest to invest in new technologies and sustainable practices.

The renewed political interest for keeping production in Europe, and for increasing resilience of farmers to be less dependent on foreign imports, could be a welcome trigger for change.

But only time will tell.

Finally, what do you see as the other major challenges affecting our agricultural systems in the coming decades? How is EurAgEng working to tackle these challenges?

Aside from the particular situations created by the pandemic and now the war, with a sincere wish this will end soon, I believe that the major challenges for agricultural systems will remain the same. These challenges are ensuring the proper management of soil, water and energy, adapting to and mitigating climate change impacts, ensuring enough food and feed production but also adequate distribution, and facilitating knowledge access and knowledge transfer to society.

EurAgEng members are working to develop innovative solutions that contribute to the efficient and better use of soil, water and energy. Some examples are the Intelligent farms, the application of circular economy principles in the sector, the enhancement of conservation agriculture practices and the awareness of the importance of a multi- and inter-disciplinary approach.

www.eurageng.eu

Thanks to the Secretary-General, Dr Ivo Hostens, for reading and contribution.

TACKLING SOIL HEALTH FROM EVERY ANGLE

Soil health is fundamental to feeding the growing human population and mitigating the most damaging effects of global climate change. Despite its importance, the complex and dynamic nature of soil means that best practices for protecting and restoring Earth's soil are not always available. By bringing together different fields and employing innovative new techniques, **Dr Christine Sprunger** and her team at The Ohio State University are gaining insights on how to improve soil health and tackle some of our planet's biggest threats.

Save Our Soils

The soil under our feet is much more important than many of us believe. Soil is not the static substance it can appear to be at first glance. Instead, soils are diverse environments for a wide variety of lifeforms, and host some of the planet's most important chemical and biological cycles. Soil also sits at the centre of many of humanity's greatest challenges, including climate change and food insecurity.

As the global human population grows, we face multiple seemingly contradictory goals. With an estimated 26.4% of Earth's population experiencing food insecurity, we need to greatly increase our global food production. At the same time, we also need to reduce the negative impact of agriculture on Earth's soils – a critical resource that is quickly becoming degraded around the world.

Over the past few decades, the major focus of conventional agriculture has been to increase crop yields. Most cropping systems involve adding synthetic fertilisers and churning up the soil between harvests, in a process known as tilling. Tilling is a common practice often used to mechanically destroy weeds and prepare the soil for planting. In the short term, tilling and adding synthetic chemicals lead to huge increases in yields; however, these practices degrade soils, causing them to lose nutrients over the long term.

As soil becomes degraded by chemical fertilisers, pesticides, tilling and other management techniques, it can lose its structure and become washed away. In fact, billions of tonnes of fertile topsoil are lost every year, and with it the crucial ecosystem services it provides, including its amazing ability to simultaneously produce food, purify water and store carbon.

Furthermore, agriculture is a major source of greenhouse gas emissions, contributing to global climate change. By increasing the severity and frequency of extreme weather events such as droughts and storms, climate change further threatens our ability to grow food. Not only do fertilisers indirectly release greenhouse gases during their manufacture, but they also directly release nitrous oxide within the soil. Nitrous oxide is a potent greenhouse gas with a warming effect 300 times that of carbon dioxide.

Healthy soil is a vital piece of the puzzle in our fight against global climate change. Not only are healthy soils more resilient to climate events, but they can actually act as a carbon sink, capturing carbon dioxide from the atmosphere and storing it in the ground as organic matter. Globally, soils store as much carbon as all plants above ground. Thus, if restored and protected, soils offer a real option for mitigating global climate change.

As soil is a complex dynamic system, it can be difficult to obtain a clear picture of what constitutes as 'healthy'. Fortunately, emerging techniques have given us new tools that allow scientists to measure soil's vital signs.

Perennial Plants and Crop Diversity

Dr Christine Sprunger and her colleagues at The Ohio State University are using new soil indicators to investigate how different management practices can lead to real improvements in soil health. In a recent study, Dr Sprunger's team examined the effects of different types and mixtures of crops on soil health.

'We have a primary goal of examining how global change biology, biodiversity, and management impact soil health and rhizosphere processes for enhanced ecological function in annual and perennial dominated landscapes,' explains Dr Sprunger.

Perennial plants are plants that live and grow year after year, as opposed to annual plants, which grow, produce seeds and die all within one growing season. Perennial plants have some advantages: they are in the soil year-round, exhibit deep root systems and biological activity, ultimately reducing erosion as the soil is never left bare.

Dr Sprunger and her colleagues used new soil health indicators that are more sensitive to changes in soil management than previous approaches. They hoped to gain a deeper understanding of soil carbon dynamics. Greater knowledge of these mechanisms would help researchers to understand exactly how soils store and release carbon dioxide, in order to find ways of maximising the amount of carbon stored. The team examined soil health indicators at the Biofuel Cropping System Experiment, a long-term experimental trial located at the W.K. Kellogg Biological Station in southwest Michigan. The experiment was established in 2009 and consists of annual row-crops, perennial grasses of just one species, and multiple species of perennial plants mixed together.

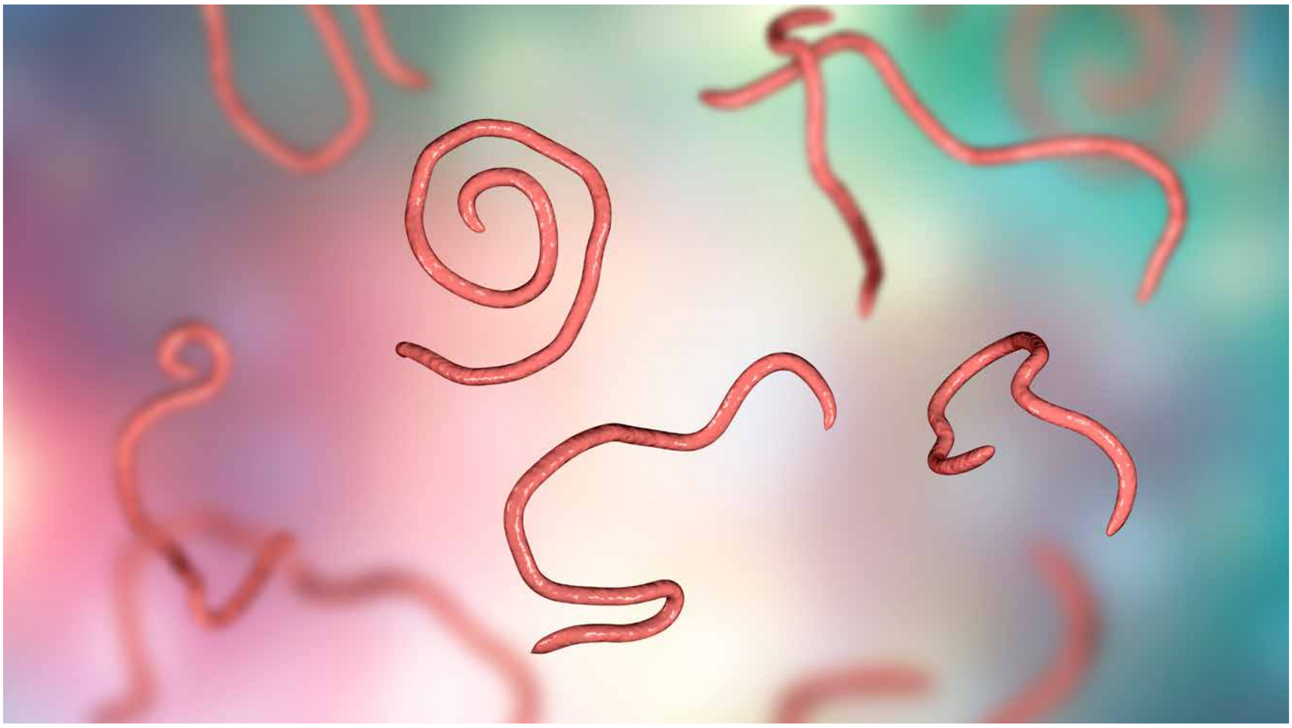
Their findings demonstrated that having a diverse mixture of different crops planted together enhanced soil health in both annual and perennial systems. They saw the largest gains in soil health in plots containing a mixture of perennial species, showing that this could be an effective strategy for stabilising carbon into the soil – allowing the soil to act as a carbon sink.

'The realisation that both perenniality and diversity are needed for accelerated accumulation of carbon is a novel finding that has important implications for land managers working to sequester carbon,' says Dr Sprunger.

Her team's study gives more evidence to core soil health practices – namely increased crop diversity, year-round cover, living roots, and reduced soil disturbance from tilling.

Science via Mail

Agricultural scientists will usually have test strips of land at their research centres to study different agricultural practices. This allows them to control various research parameters, so that they can isolate the benefits and disadvantages of each different factor. However, such studies can often fail to capture all of the different, complex and complementary approaches that farmers use to manage their land. Therefore, on-farm studies can offer a much more realistic picture when assessing the effects of farming practices.



Therefore, Dr Sprunger and her colleagues sought to find evidence for how different organic farming practices affect soil health in the context of real farms. 'I work on interdisciplinary teams to assess how management impacts soil health on local and regional scales,' says Dr Sprunger. 'Linking management practices to soil health outcomes at regional scales has rarely been done, making this work extremely innovative.'

The team wished to determine which organic farming practices are best suited to which soil types using data collected from real working farms. However, practical constraints usually mean that a study like this can only be conducted on a very small number of farms. The team had an ingenious solution to this issue: mail-in soil. The team asked farmers to collect samples of their soil and mail them to the university for analysis.

Using this novel method, her team collected 195 samples from organic cornfields across Michigan, Indiana, Ohio, and Pennsylvania. This alone would provide useful data, but by combining it with surveys on the farmers' management practices, the team could tease apart the complex interactions between soil type, management practices and soil health.

Dr Sprunger showed that in a farm setting, increasing the diversity of crops was not enough. In fact, the farmers that had the best soil health indicators not only grew diverse mixtures of perennial species, but they also practised low tillage to minimise soil disturbance.

Planet of the Worms

Dr Sprunger and her lab noticed that most soil health research focuses only on bacteria and fungi, opening up new opportunities for investigating different organisms. 'Our lab has recognised an important need in developing nematodes as a potential indicator of soil health,' says Dr Sprunger.

Nematodes are microscopic worms found in soils across the world. These tiny worms are so ubiquitous, that it has been estimated that about four out of every five animals on Earth are nematodes. Nematodes live short lives, so their numbers respond quickly to changing environmental conditions. In addition, they feed on fungi and bacteria, and play numerous roles in soil cycling.

Dr Sprunger's work is also gaining attention: she has been awarded a total of six grants to further explore nematodes as a potential indicator to assess ecosystem health. Findings from her team reveal that nematodes reflect how the nutrients in the soil are changing, offering important insights into the nitrogen and carbon cycles.

The Future of Soil

Climate change and conventional agricultural practices pose serious threats to one of our planet's greatest assets: its soil. As extreme weather events increase in frequency, we need a deep understanding of how our soil will be affected. Dr Sprunger and collaborators have also received a large grant from the National Institute of Food and Agriculture to explore flooding impacts on soil dynamics in corn fields.

The health of Earth's soils is fundamental to our ability to produce food in the face of climate change and other threats. However, with a deeper understanding of soil dynamics, we could transform humanity's future on this planet, by enabling the soil to work as a carbon sink, and recovering damaged soil ecosystems – all while increasing global crop yields.

Meet the researcher

Dr Christine Sprunger
School of Environment and Natural Resources
The Ohio State University
Wooster, OH
USA

Dr Christine Sprunger gained her PhD in Crop and Soil Sciences and Ecology, Evolutionary Biology, and Behavior at Michigan State University in 2015. Upon graduating, she became an NSF Postdoctoral Fellow in Biology at the Agriculture and Food Security Center at Columbia University.

Dr Sprunger then moved to The Ohio State University to work as a Postdoctoral Research Scientist in the School of Environment and Natural Resources. She now works in her current position as Assistant Professor of Soil Science and Rhizosphere Processes in the same department. In her research, Dr Sprunger focuses on interactions between soil, plants, water, animals and humans, and how we can build resilience in our agricultural systems in the face of a changing climate. Starting from August 2022, Dr Sprunger will be joining the Department of Plant, Soil, and Microbial Sciences and the Kellogg Biological Station at Michigan State University as an Assistant Professor of Soil Health.

CONTACT

E: sprunger.29@osu.edu
E: sprunge5@msu.edu
W: www.sprungerlab.com

KEY COLLABORATORS

Steve W. Culman, The Ohio State University
Tvisha Martin, The Ohio State University
Meredith Mann, The Ohio State University
Prabhjot Singh, The Ohio State University
Doug Jackson-Smith, The Ohio State University
Leo Diess, The Ohio State University
Caroline Brock, University of Missouri
Jordon Wade, University of Missouri

FUNDING

Great Lakes Bioenergy Research Center, U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research (Award DESC0018409).

National Science Foundation Long-term Ecological Research program (DEB 1832042).

US Department of Agriculture NIFA Organic Agriculture Research & Extension Initiative (2014-51300-22331).

FURTHER READING

T Martin, J Wade, P Singh, CD Sprunger, The integration of nematode communities into the soil biological health framework by factor analysis, Ecological Indicators, 2022, 136, 108676. https://doi.org/10.1016/j.ecolind.2022.108676.

CD Sprunger, SW Culman, L Deiss, C Brock, D Jackson-Smith, Which management practices influence soil health in Midwest organic corn systems?, Agronomy Journal, 2021, 113, 4201–4219. https://doi.org/10.1002/agj2.20786

CD Sprunger, T Martin, M Mann, Systems with greater perenniality and crop diversity enhance soil biological health, Agricultural & Environmental Letters, 2020, 5, e20030. https://doi.org/10.1002/ael2.20030

'GREEN MANURE': HOW COVER CROPS CREATE HEALTHY SOILS AND BOOST CROP YIELDS

In order to meet the demands of a growing human population, farmers across the globe are attempting to improve the yields and nutritional content of their crops. However, this is an especially difficult challenge, in an age where climate change is negatively impacting our agricultural systems. To address these pressing issues, **Dr Lynn Brandenberger** and **Dr Joshua Massey** of Oklahoma State University focus on the intersection of soil health and crop production. Recently, they demonstrated how cover crops can greatly improve soil health and, consequently, enhance crop yields.

Soil Health = Crop Health

In the US, many regions that were reliable sources of crops now have reduced acreage available for food production. This is due to many causes, including farmland lost to urban sprawl, drought in the western US, and the high cost of conventional farming methods.

Furthermore, practices such as continuous use of clean-tillage, a mechanical means of disturbing bare earth in preparation for planting, have resulted in soils that are less productive due to the loss of soil organic matter, and subsequently to the loss of productive farms. Therefore, farmers in the US are beginning to consider how soils can be managed using more sustainable approaches.

Soil health can be thought of as a combination of the chemical, physical and biological properties of the soil. Heavy fertiliser use, tillage, and periods of uncovered bare earth between harvest times can lead to changes in soil chemical properties, such as the amount of nutrients and carbon in the soil. In fact, with conventional clean-tillage farming, the soil's available nutrients quickly decline to levels that cannot support most crop plants. Physical properties important for soil health, including water-holding capacity, chemical properties such as nutrient retention and availability, and biological properties, such as the diversity of soil microorganisms, also decline with conventional clean-tillage farming.

Soil organic matter, which includes the decomposing remains of plants and animals, influences all three aspects – chemical, physical and biological – of soil health. Soil organic matter contributes to the physical structure by helping soil particles to be aggregated allowing for better water infiltration, prevents erosion, and facilitates improved plant root growth. Organic matter also stores and releases nutrients, increases water availability for crops, and provides food for beneficial fungi, bacteria and worms that form critical relationships with the plants.

Dr Joshua Massey and Dr Lynn Brandenberger of Oklahoma State University are interested in the intersection of soil health and crop quality. Since effective and sustainable farming practices should work to optimise soil properties, their work focuses on developing farming methods that maintain and increase levels of soil organic matter. As the global population grows and climate change threatens our ability to grow crops, such sustainable

farming methods are vital for producing high yields of crops for years to come.

Cover Crops

In particular, Dr Brandenberger, Dr Massey and their colleagues focus on how 'cover crops' can increase the organic matter content in soil. Cover crops are planted to cover the soil between cycles of growing food crops, and have been shown to prevent soil erosion, improve soil fertility and quality, and reduce the incidence of pests and disease.

In a recent five-year-long study, the team created three cover crop combination treatments in a field where spinach, sweet potato, and cowpea were grown. In addition to the cover crop plots, they created a control plot, in which no cover crops were planted between harvests and the soil was left bare, just like in a clean-tillage system. The team measured multiple variables related to soil and plant health and monitored the yield of the three cash crops. The results of the study suggest that the cover crop treatments can increase soil organic matter, though the resulting effects on crop yield may take more time to measure.

Cover Crops Increase Nutrient Availability

Farmers have used multiple methods to increase soil organic matter; for example, by adding compost, manure, or organic fertiliser to their soil. However, each of these additives comes with the cost of material supplies, as well as other problems such as the potential for food-borne disease. Maintaining cover crops ensures that the earth is never bare and provides the soil with organic matter as the plants die and decompose, offering a much simpler and cheaper method of maintaining soil organic matter.

In their study, Drs Massey, Brandenberger and their colleagues rotated cover crop species between winter and summer seasons within each plot. By varying the cover crops, the researchers could also determine which combination of winter and summer cover crops are most compatible and effective at improving soil health and crop yield.

The amount of soil organic matter, determined by standard laboratory practices for quantifying carbon in the soil, was measured in all four areas annually from 2016 to 2020. The team also tracked nitrogen (N), phosphorus (P) and potassium (K) – three important nutrients for plants. They began to notice a change in organic matter starting in 2019, with the non-cover cropped control plot having the lowest level of organic matter.

After monitoring in 2020, there were significant differences in soil organic matter, N, P and K between the first cover crop treatment area and the control plot, with the control plot having the least amount of nutrients and organic matter of all the plots. However, there were no significant differences between the control plot and the remaining two cover crop treatment combinations, potentially indicating that the first crop area had the most effective combination of cover crop species.

Effects on Crops Yields Yet to Come

The researchers hypothesised that the yields and nutritive value of spinach, cowpea and sweet potato would be increased as a consequence of directly seeding new crops into fields where cover crops had been grown. Although they did not find any significant differences in the yields of spinach or sweet potato, the team did measure significant differences in the yield of cowpea, with the control plot yielding significantly less than some of the cover crop plots.

It is important to recognise that organic matter can take decades to accumulate. Since the researchers only noticed a trend toward the fourth and fifth years of monitoring, it is likely that they only captured the beginning of the effects that cover crops can have on crop yields. Additionally, when looking at the data collected since 2016, the control plot continued to decline in all measurable nutrients and organic matter. This trend is likely to continue, potentially manifesting in significant differences in soil organic matter between all cover crop combinations and the control plot.

Thus, the researchers stress that although they did not find any significant differences in marketable number and weight of sweet potatoes or spinach between the plots, the differences in nutrient availability and organic matter are likely to manifest as improved crop yields over the next few years.

Benefits to Soil Structure and Biodiversity

Keeping cover crops growing rather than leaving bare soil also has consequences for the physical health of the soil. For example, other researchers have demonstrated that cover crops improve the porosity of the soil, improving water infiltration and movement into plants. The soil structure also becomes more aggregated and stable, improving root penetration.

In some studies, these changes in the soil have been linked to improved yields of crops such as soybeans. To assess the physical structure of the soil, Brandenberger, Massey and their colleagues aim to evaluate variables including hydraulic conductivity, to assess water infiltration between each cover crop growth cycle. They also plan to measure soil compaction and aggregate stability using standard techniques in soil science.

Cover crops also provide food for the rich biodiversity found in soil. Since organisms in the soil are important drivers of soil function and health, their importance should not be understated. In fact, soil is by far the most biodiverse ecosystem on the planet, home to a diverse array of bacteria, fungi and animals. Furthermore, soil organisms break down organic matter into available nutrients for plants and replenish organic matter as plants consume soil elements. Therefore, to see whether this biological activity was increasing in the cover crop plots, the team will assess microbial respiration, by measuring amount of carbon dioxide given off by soil microbes.

Integrating Science with Management

There is evidence that cover crops have been used for centuries by ancient agricultural communities including the Romans and the Ancient Chinese. Although the advent of conventional large-scale farming techniques has certainly improved crop yields in the short term, allowing billions of people to be fed, we have lost many traditional agricultural practices that help keep farming sustainable, including the use of cover crops.

Now, the research of Drs Brandenberger, Massey and their colleagues is showing us how cover crops can greatly improve soil health in the long term, making our farming practices more sustainable. By further assessing soil health and crop yields in the experimental plots over the next few years, the researchers hope to develop guidelines for farmers who wish to integrate cover crops into their production systems, allowing them to achieve higher yields of crops in a sustainable fashion for decades to come.

Meet the researchers

Dr Lynn Brandenberger
Department of Horticulture and Landscape Architecture
Oklahoma State University
Stillwater, OK
USA

Dr Lynn Brandenberger has worked to support the commercial farming community of Oklahoma for more than two decades. With a PhD in Plant Science from the University of Arkansas, Dr Brandenberger began working as an extension vegetable crop specialist with Texas A&M University in 1992 and subsequently began as an associate professor at Oklahoma State University in 2001. Currently he is a full professor and research specialist in the Horticultural Food Crops Extension program. Dr Brandenberger is passionate about providing best practice methods to the local vegetable industry. He has also spent several seasons serving as the advisor for a study abroad program that worked with rural villagers in Guatemala.

CONTACT

E: lynn.brandenberger@okstate.edu
W: https://experts.okstate.edu/lynn.brandenberger

Dr Joshua Ryan Massey
Cimarron Valley Research Station
Oklahoma State University
Stillwater, OK
USA

Dr Joshua Massey was awarded his Master of Science in Agronomy from Kansas State University in 2005, and recently received his PhD in Soil Science from Oklahoma State University. While carrying out his PhD project, he also worked as the Senior Station Superintendent at the Cimarron Valley Research Station of Oklahoma State University, which focuses on research for agronomic and horticultural crops – a position he still holds. Dr Massey has authored several peer reviewed publications and research reports, and has laboratory teaching experience at Oklahoma State University and other institutions.

CONTACT

E: josh.massey@okstate.edu
W: https://agresearch.okstate.edu/people/josh-massey/index.html

KEY COLLABORATORS

Hailin Zhang, Oklahoma State University
João Antonangelo, Oklahoma State University
Lynda Carrier, Oklahoma State University
Matt Beartrack, Oklahoma State University

FUNDING

Oklahoma Department of Agriculture, Food, and Forestry

AGRICULTURAL RESEARCH TODAY FOR A BETTER FUTURE TOMORROW

How to support the expanding human population is one of the greatest societal challenges in the 21st century. To meet the demand for food, fuel and fibre, agricultural productivity will need to dramatically increase. However, to ensure long-term sustainability and resilience, increased productivity must not sacrifice the health of the surrounding ecosystems. Led by Dr Dennis Busch and Dr Andrew Cartmill, the University of Wisconsin-Platteville's Agro-Ecosystem Research Program draws on the expertise of local and international collaborating scientists and farmers to develop alternative agricultural practices that support sustainable intensification for future food security.

Sustainable Agricultural Intensification

The rapidly expanding human population is estimated to reach 9 billion by the year 2050. That's 1.5 billion more mouths to feed in just 30 years, on a planet with resources that are already overstretched. To meet these demands, agriculture will not merely have to maintain current levels of productivity – it will have to greatly exceed current levels. It is expected that by 2050, over 80% of agricultural production will come from land that is currently cultivated.

Conventional agricultural intensification, which has allowed us to increase yields to current levels over the last few decades, is frequently associated with practices that degrade the environment. These practices, such as increasing application of chemical fertilisers, may help to increase yields over the short-term, but they are much like borrowing from tomorrow to pay for today.

Conventional intensive farming leads to the degradation of 'ecosystem services' – such as natural pest control and productive soils – eventually meaning that maintaining the same yields is impossible, no matter how much extra fertiliser is added to the system.

Climate change, increased urbanisation, environmental degradation, and increased municipal and industrial competition for finite resources place additional pressure on agricultural systems, threatening their long-term sustainability and resilience.

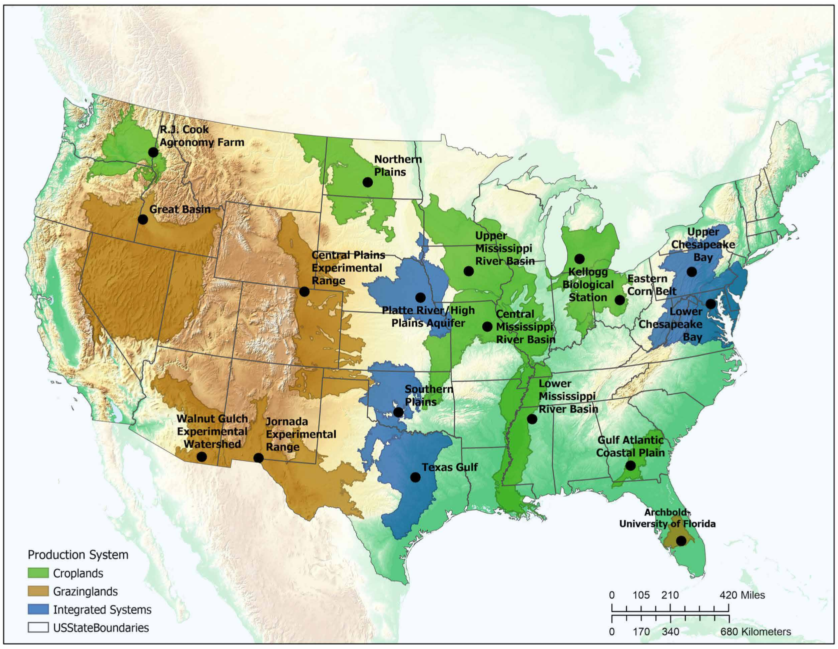
To intensify agriculture in a sustainable way, alternative practices that support healthy ecosystems are vital. Taking care of the 'agro-ecosystem' – the farm and surrounding natural habitats – requires holistic approaches.

'Agroecology, which is the study of farming within a system, is understanding that farming is not separate from the landscape. It's "big picture" thinking. It's relating everything back together. Not just the fertiliser, not just the yield, but also how your plants or your farm adds value back to the landscape,' explains Dr Andrew Cartmill of the University of Wisconsin-Platteville (UW-Platteville).

Dr Dennis Busch and Dr Cartmill have been investigating which alternative agricultural practices offer whole system improvements to agro-ecosystem health. In their Agro-Ecosystem Research Program, Dr Busch and Dr Cartmill have been collaborating with local, national, and international farming groups and scientists to gather

the evidence needed to develop farming Best Management Practices.

The program consists of multiple projects – funded by a variety of external agencies, including the USDA's National Institute of Food and Agriculture – addressing important research areas, such as reducing and eliminating water contamination and greenhouse gas emissions from farms in the US Midwest, investigating how cattle grazing can play a role in sustainable agricultural practices, and exploring how farms with equipment to monitor environmental health ('instrumented farms') can supply the evidence needed to sustainably intensify agriculture.



The LTAR network comprises 18 locations distributed across the US working together to address national and local agricultural priorities and advance sustainable agricultural intensification.

The overarching aim of UW-Platteville's Agro-Ecosystem Research Program is to work towards achieving the 'three pillars' of sustainability– environmental, economic, and social – to ensure the resilience of agricultural communities and our future food security. To achieve this goal, the program draws on the expertise of a multidisciplinary team and focuses on three core areas – research, outreach, and education.

It's All about Networking

By collaborating with farming networks, the Agro-Ecosystem Research Program accesses a stream of high-quality primary data from instrumented farms that underpins the information-driven approach of the projects. 'This approach will also allow for the assessment of the reaction of local farmers to future scenarios, create buy in, mediate iterative discussion and provide a unique multi-facet approach to educate students in real world applied farming issues,' says Dr Busch.

Locally, the team has partnered with research farms that facilitate plot-level experiments, allowing them to investigate multiple or 'risky' practices before expanding promising methods to field-scale trials. The team has also formed partnerships with the Soil and Water Health Coalition, Illinois, and the Lafayette Ag-Stewardship Alliance, Wisconsin – both farmer-led non-profit organisations committed to sustainable agriculture and resource conservation. Across the regional and continental scale, the USDA Long Term Agroecosystem Research network includes 18 research units strategically located across the US focused on addressing questions of sustainability and resilience in agricultural systems. This collaboration allows the researchers to engage in synergistic, nationwide research activities.

Internationally, the Global Farm Platform network provides eight strategically-placed farm platforms, including the UW-Platteville Pioneer Research Farm, dedicated to the sustainable intensification of grazing livestock production. This has provided the Agro-Ecosystem Research Program team with access to a global academic network to support research and education. These farm platforms are located in the US, South America, the United Kingdom, India, Australia, and New Zealand.

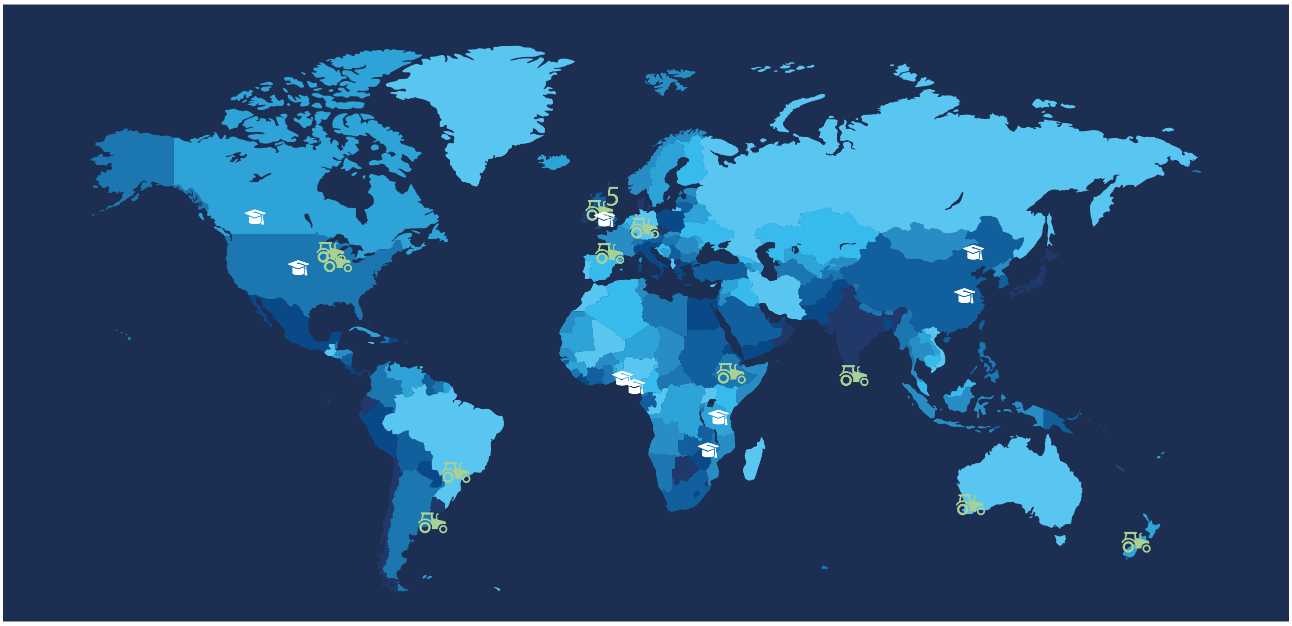
Collecting the Evidence

The research team, students, and collaborating partners measure numerous environmental health indicators to assess the effect that different agricultural practices have on the surrounding ecosystems.

For example, the use of 'cover crops', which involves cultivating plants in between growth cycles of food crops, can improve soil nutrient levels, enhance the amount of carbon sequestered and stored in soil, reduce soil erosion, and improve water cycling. However, choosing which cover crops to use, when to plant them, when to harvest, and what practices to use alongside the chosen cover cropping method are decisions that require reliable evidence about their impact on the agro-ecosystem.

Quantifying the effects of different agricultural practices takes the guesswork out of selecting the most appropriate methods to support sustainable production. Combining environmental measurements with those of economic performance, such as crop yields or livestock growth and weight, helps the researchers find the right balance that ensures future economic viability and food security. Dr Busch and Dr Cartmill have devised research projects that address urgent and important local and regional needs. 'While global issues of long-term food availability and security are driving forces in developing national policy and research priorities, it is the regional and local environmental issues that have been the primary impetus for action among the local farming community,' explains Dr Cartmill.

'The issues of concern voiced by our collaborating farmer-led groups include elevated nitrate concentration in groundwater, soil loss from cropland, and nitrogen loading to the Gulf of Mexico,' he continues. Excess nitrogen from chemical fertiliser usage leaches from farmlands into the surrounding



Farm platforms and academic partners involved in the program.

waterways, causing a deadly low-oxygen zone that makes coastal habitats hostile to marine life.

A report in 2018 estimated that 70% of the nitrogen and phosphorous in the Gulf of Mexico originates from agricultural sources, which reaches the gulf via the Mississippi River. Wisconsin, Illinois and Iowa are particularly susceptible to contributing excess nutrients to groundwater and waterways due to the naturally shallow depth of the soils in these regions.

The multidisciplinary Agro-Ecosystem Research Program team – which incorporates natural scientists, engineers, social scientists, and economists – aims to find practical solutions to eliminate water contamination from farms in the Midwest states. In time, these techniques could be extrapolated to farms across the rest of the US and the world.

Education and Outreach

As part of the program's educational objectives, undergraduate students on UW-Platteville's agricultural courses participate in field data collection and laboratory analysis while designing and developing their own real-world research under the guidance of Dr Cartmill, Dr Busch and their team.

With access to local, national, and international partners, students can undertake short-term research experiences from locations across the globe, giving them a fantastic opportunity to align their work with their individual interests. Students improve their communication skills, gain leadership experience, enhance their critical thinking, and improve their ability to synthesise information through these experiences.

Developing sustainable and productive agricultural practices is an ongoing process, unlikely to provide all the solutions overnight, training a qualified and skilled workforce that can continue this research in the decades to come is vitally important. In addition to UW-Platteville's established courses and modules, such as Crop Science and Weed Science, the Agro-Ecosystem Research Program is providing the scope for the team to develop a dedicated Freshwater University.

UW-Platteville is ideally situated for freshwater research and training, and the Freshwater University will coalesce the strength, diversity, and collective resources of the University of Wisconsin System. Dr Busch and Dr Cartmill have been generating real-world, hands-on datasets through the Agro-Ecosystem Research Program that will form the basis of the existing and new courses to be included in the Freshwater University syllabus.

The farms used to evaluate alternative agricultural practices also serve as an engagement tool. A key component of the Agro-Ecosystem Research Program is effective and productive outreach activities. The three pillars of sustainability – environmental, economic, and social – rely on largescale uptake of alternative agricultural practices by farmers. Thus, increasing the reach of the program could positively influence perception and subsequent uptake of these methods.

Results obtained from the demonstration plots are included at field days, meetings, and newsletters. For example, in a recent field day in Jo Daviess County, Illinois – hosted virtually due to COVID-19 – researchers, crop advisors, and students covered topics including the value of cover crops, results and plot details from nitrogen research, and soil health and water quality results from the demonstration plot.

By incorporating education and outreach activities alongside the research, the Agro-Ecosystem Research Program has the potential to affect real change by starting a global agricultural revolution – one farm at a time.

Meet the researchers

Dr Dennis L. Busch
University of Wisconsin-Platteville Pioneer Farm
Platteville, WI
USA

Dr Dennis L. Busch holds the position of Research Director at UW-Platteville Pioneer Farm, managing research projects related to dairy pasture forage, surface water runoff, and also devoting time to supervising student researchers. A Wisconsin native, he achieved his undergraduate BS in agricultural business and MS degree in agricultural industries from UW-Platteville, and earned his PhD in water resources science from the University of Minnesota-Twin Cities. Dr Busch teaches undergraduate modules in Agricultural Hydrology, Water Quality, and Agroecosystem Research.

CONTACT

E: buschd@uwplatt.edu
W: https://www.uwplatt.edu/profile/buschd

Dr Andrew D. Cartmill
School of Agriculture
University of Wisconsin-Platteville
Platteville, WI
USA

Dr Andrew D. Cartmill earned his PhD in horticulture from Texas A&M University, before continuing his research at Texas A&M and at the University of Wisconsin-Platteville. Within the latter's Department of Soil and Crop Science, he currently holds the position of Assistant Professor. Dr Cartmill's research interests focus on sustainable agriculture and ecological topics, including crop and fungal mycorrhiza associations, plant responses to environmental stress, water quality, and plant nutrition. In addition to his research activities, Dr Cartmill teaches across a range of undergraduate modules in UW-Platteville's School of Agriculture, including Crop Production and Agroecology.

CONTACT

E: cartmilla@uwplatt.edu
W: https://www.uwplatt.edu/profile/cartmilla

KEY COLLABORATORS

Dr Thomas B Moorman, USDA ARS
Professor Michael Lee, Harper Adams University
Dr Donita L. Cartmill, UW-Platteville

FUNDING

USDA - National Institute of Food and Agriculture (NIFA)

UNIVERSITY OF WISCONSIN PLATTEVILLE

ltar Long-Term Agroecosystem Research

GLOBAL FARM PLATFORM Towards Sustainable Ruminant Production

BIOENGINEERED COTTON COULD HELP SOLVE WORLD HUNGER

Humans have relied on cotton's textile fibre for nearly seven millennia. However, utilising cottonseed as food has been a long and unfulfilled goal of many plant breeders. Along with its abundant, high-quality protein, cottonseed also contains gossypol – a toxic chemical that renders the seed inedible. Cottonseed's fate as a mostly unusable by-product seemed sealed until **Dr Keerti Rathore**, a professor at Texas A&M University, announced that he had successfully created gossypol-free cottonseed. Dr Rathore's tireless devotion has given the world the potential to significantly improve food security

The cotton plant produces the most significant volume of natural fibre in the world. Grown in over 70 countries, more than 20 million farmers cultivate and depend on cotton for their livelihood. Yet, for every 1 kilogram of fibre, 1.65 kilograms of cottonseed go mostly underutilised. The reason is simple: cottonseed also contains the compound gossypol, which is toxic if consumed above safe levels.

A natural chemical produced in the pigment glands of the cotton plant, gossypol protects the cotton plant from microbial infections and being eaten by insect pests. Ruminants such as cattle can eliminate the threat – both by degrading gossypol and by binding it to proteins. However, humans and other single-stomached animals including pigs, birds and fish are sensitive to gossypol. In high concentrations, gossypol can cause heart and liver damage and blood disorders.

Although cottonseed oil, with gossypol removed during processing, is used in frying and baking, its abundant protein is currently only used for cattle feed. For many scientists, our under-utilisation of cottonseed represents a lost opportunity to address global hunger issues. Scientists estimate that the current rates of cottonseed production could fulfil the protein requirement of over 500 million people worldwide, many of whom live in cotton-producing countries, such as India and Pakistan. With an estimated 700 million people suffering from global hunger and malnutrition, toxin-free cottonseed could significantly improve global nutrition security.

In 2006, after decades of failed efforts to breed gossypol-free cottonseed and to eliminate the toxin on a commercial scale, positive news came out of Texas A&M University when Dr Keerti Rathore announced that his lab had successfully disrupted gossypol production in cottonseed. His team's genetically modified cottonseed has since survived significant regulatory hurdles to achieve approval in the US. The story speaks of the ground-breaking nature of the discovery, as well as the intense regulatory hurdles involved in receiving government approval to cultivate genetically modified crops.

Top: Seeds from normal parental plant. Bottom: Seeds from engineered and deregulated TAM66274 plant.

Dr Rathore (middle), with his associates LeAnne Campbell and Devendra Pandeya. CREDIT: Tim Douglass.

Silencing Gossypol Genes

Efforts to eliminate gossypol from cottonseed began in earnest in the 1990s. Armed with essential gene sequences involved in gossypol production, scientists from all over the world set out to use novel gene silencing technologies to disrupt the biosynthesis pathway that leads to gossypol production. Although these initial efforts did not successfully reduce gossypol production, Dr Rathore continued to experiment with novel gene silencing methods.

In 2004, his team initiated a new round of experiments that differed from others in a critical way; this time, the group used a tool called RNA interference (RNAi) to try to silence gossypol synthesis-related genes. This technology degrades messenger RNA, a molecule that copies the code contained in DNA to create proteins. Dr Rathore leveraged this technology to selectively interfere with gossypol gene expression in the seed. This targeted approach meant that gossypol could still be produced in the cotton stems, leaves and roots, where it provides essential anti-microbial and pest-protection functions. Dr Rathore named his team's cotton trait 'Ultra-Low Gossypol Cottonseed' (ULGCS).

Before this discovery, RNAi-mediated silencing was not believed to be capable of silencing genes in one part of the plant without spreading to other parts of the plant. 'Our work has shown that such a spread of silencing is not always the case and that such an RNAi-mediated trait is generationally stable,' says Dr Rathore. This type of tissue-specificity is ground-breaking – a feature that even the famed gene-editing tool CRISPR cannot boast.

After examining the trait in cotton crops under field conditions and confirming it could be passed on from generation to generation, Dr Rathore reported more promising news: ULGCS cotton fibre yield and quality did not differ from that of regular cotton. After more than a decade of work, it became clear that ULGCS cotton had the potential to be commercially viable.

Jumping Regulatory Hurdles

Successfully growing and cultivating the novel cotton in relatively small field settings was a significant accomplishment. However, receiving regulatory approval for its commercial use represented an entirely new type of challenge.

In the US, genetically modified crops are subject to intense regulatory scrutiny to ensure that they are safe for the environment and human health. ULGCS cotton was initially considered a regulated article by the United States Department of Agriculture - Animal and Plant Health Inspection Service (USDA-APHIS), meaning it could not be freely cultivated. However, Dr Rathore knew that this technology could become a globally critical food source. Without deregulated status that allows for general cultivation, ULGCS cotton would be stuck in regulatory limbo, unable to fulfil its potential.
After scrupulous field and lab studies designed to evaluate the integrity of the genetic changes and the plant's performance in the field, Dr Rathore and his colleagues submitted a petition to make one of the ULGCS lines, TAM66274, a deregulated entity. The data was on their side: all analyses demonstrated that seed gossypol had been reduced by up to 97% in TAM66274, with the remaining concentration well below established safety thresholds.

In 2018, APHIS concluded that the modified cotton should be deregulated, with the justification that it does not pose any risk to the health of humans, animals, or the environment. A year later, the ULGCS line TAM66274 experienced another potent victory: the US Food and Drug Administration (FDA) assessed gossypol levels in ULGCS to be safe for use as food and animal feed.

After decades of academic research and subsequent years of cooperation and collaboration with regulatory agencies, Dr Rathore enabled the distribution of this new cottonseed within the US. His efforts cannot be understated; usually, these types of genetically modified traits are limited to biotech companies that have tens of millions of dollars available to push the product through expensive and lengthy regulatory processes. Until 2019, ULGCS was only the fourth genetically modified organism developed by a university scientist to obtain regulatory approval in the US.

Two key collaborators, Kater Hake (left) and Thomas Wedegaertner (middle), inspecting one of the team's regulatory field trials in North Carolina.

Handful of ULGCS kernels.
CREDIT: Beth Ann Luedeker.

Socioeconomic Implications

The real benefit of ULGCS lies in the fact that it is already a by-product of a plant cultivated globally. Cotton fibre will remain the primary product of any cotton crop, including genetically modified plants. Since its production comes at little additional expense to farmers, ULGCS will naturally out-compete other vegetable protein sources in terms of price and sustainability metrics. Its low production cost and high-quality protein make ULGCS a potent tool in the fight against global hunger and protein malnutrition, a problem that still plagues one in nine people.

Along with direct human consumption, ULGCS can also be used indirectly to positively impact human nutrition. In several trials, ULGCS was found to be an adequate feed for aquaculture species. While cattle must eat 20 kilos of protein to create 1 kilo of edible beef protein, chicken and fish have a much lower ratio, using only 4.6 kilos of plant protein to create 1 kilo of animal protein. Currently, both poultry and aquaculture industries are in dire need of alternative sources of protein to keep up with the exploding demand for eggs and meat, mainly in developing countries.

Cattle also take an enormous toll on the environment, as they emit potent greenhouse gases, and require more land and feed. Additional sources of cheap, effective feedstock will ease pressure on current feed sources, particularly in aquaculture and poultry, creating more feasible ways to capitalise on these sustainable food sources. Finally, since its production does not require additional land beyond what is already used for cotton, protein derived from ULGCS does not create extra strain on the environment. In fact, its widespread use should ease pressure on forests and the ocean's fish, which are both overexploited to obtain feed for poultry and aquaculture. Farmers who already grow cotton will obtain a whole other crop with very little up-front investment.

The New Green Revolution

According to Dr Rathore, 'ULGCS offers an example that demonstrates the ability of biotechnology tools to solve a problem that traditional plant breeding cannot solve.' Even agronomist Dr Norman Borlaug, the 'Father of the Green Revolution', recognised the potential of gossypol-free cottonseed. Dr Borlaug was an impactful researcher who developed various high-yielding wheat varieties, spurring similar innovations in rice production that led to dramatic increases in grain yields in the 1950s and 1960s.

Termed the 'Green Revolution', the rampant output of these new crops helped draw millions out of malnutrition. Dr Rathore points to Dr Borlaug as an inspirational figure, attesting that 'He encouraged me to continue the work despite many failures, setbacks and lack of funding during the first ten years of the project.'

The global community will continue to benefit tremendously from Dr Rathore's demonstrated persistence as he works toward the ultimate goal: worldwide adoption and cultivation of his new cottonseed. His research will also be felt beyond the world of cotton production. By shedding light on the potential of RNAi technology, Dr Rathore has opened the door for other scientists to create innovative solutions for agricultural and global health issues. This movement very well could lead to the next Green Revolution.

Meet the researcher

Dr Keerti S Rathore
Department of Soil & Crop Sciences
Texas A&M University
College Station, TX
USA

Dr Keerti S Rathore has spent three decades fuelled by a focused purpose: developing and using genetic tools to sustainably feed a burgeoning global population. As the son of a doctor in rural India, Dr Rathore saw the effects of malnourishment first-hand. These early experiences laid the foundation for a future of work addressing key global hunger issues with biotechnology. In 1995, only a few months into his position as a Scientist at the Texas A&M University, he began research on his most ground-breaking project – developing a genetically engineered cottonseed safe for human consumption. Since then, he has become a Professor in the Department of Soil and Crop Sciences at Texas A&M and has received eleven patents, several related to his work on cottonseed. With over three decades of experience, Dr Rathore is a sought-after and globally recognised instructor and researcher in biotechnology.

CONTACT

E: rathore@tamu.edu
E: Keerti.Rathore@ag.tamu.edu
W: https://soilcrop.tamu.edu/people/rathore-keerti/

KEY TEAM MEMBERS

Ms LeAnne Campbell
Dr Devendra Pandeya

KEY COLLABORATORS

Dr Robert D Stipanovic, United States Department of Agriculture-Agricultural Research Station
Dr Lorraine Puckhaber, United States Department of Agriculture-Agricultural Research Station
Mr Thomas C Wedegaertner, Cotton Incorporated
Dr Kater Hake, Cotton Incorporated

FUNDING

Cotton Incorporated, North Carolina, USA, Texas A&M AgriLife Research

FURTHER READING

KS Rathore, D Pandeya, LM Campbell, TC Wedegaertner, LS Puckhaber, RD Stipanovic, JS Thenell, S Hague, K Hake, Ultra-Low Gossypol Cottonseed: Selective gene silencing opens up a vast resource of plant-based protein to improve human nutrition, Critical Reviews in Plant Sciences, 2020, 39, 1-29. doi.org/10.1080/07352689.2020.1724433

MS Alam, WO Watanabe, PM Carroll, JE Gabel, MA Corum, P Seaton, TC Wedegaertner, KS Rathore, MK Dowd, Evaluation of genetically improved (glandless) and genetically modified low gossypol cottonseed meal as alternative protein sources in the diet of juvenile southern flounder Paralichthys lethostigma reared in a recirculating aquaculture system. Aquaculture 2018, 489, 36-45. doi.org/10.1016/j.aquaculture.2018.02.006

CM Richardson, AJ Siccardi, SR Palle, LM Campbell, L Puckhaber, RD Stipanovic, TC Wedegaertner, KS Rathore, TM Samocha, Evaluation of Ultra-low Gossypol Cottonseed and Regular Glandless Cottonseed Meals as Dietary Protein and Lipid Sources for Litopenaeus vannamei Reared Under Zero-Exchange Conditions, Aquaculture Nutrition, 2016, 22, 427-434. doi.org/10.1111/anu.12261

SR Palle, LM Campbell, D Pandeya, L Puckhaber, LK Tollack, S Marcell, S Sundaram, RD Stipanovic, L Hinze, TC Wedegaertner, KS Rathore, RNAi-mediated Ultra-low Gossypol Cottonseed Trait: Performance of Transgenic Lines under Field Conditions, Plant Biotechnol J, 2013, 11, 296-304. doi.org/10.1111/pbi.12013

KS Rathore, S Sundaram, G. Sunilkumar, LM Campbell, L Puckhaber, S Marcell, SR Palle, RD Stipanovic, TC Wedegaertner, Ultra-low gossypol cottonseed: generational stability of the seed-specific, RNAi-mediated phenotype and resumption of terpenoid profile following seed germination, Plant Biotechnol J, 2012, 10, 174-183. doi.org/10.1111/j.1467-7652.2011.00652.x

G Sunilkumar, LM Campbell, L Puckhaber, RD Stipanovic, KS Rathore, Engineering cottonseed for use in human nutrition by tissue-specific reduction of toxic gossypol, PNAS, 2006, 103, 18054. doi.org/10.1073/pnas.0605389103

CREATING POWER FOODS WITH GENE TECHNOLOGY

At least 820 million people suffer from hunger and malnutrition globally and human population growth is likely to exacerbate this problem in the future. It is becoming increasingly important to develop sustainable and efficient methods to meet food demands. To address this global issue, **Dr Sanju A. Sanjaya** and **Bagyalakshmi Muthan** from West Virginia State University and their colleagues from Michigan State University have developed genetic technologies to improve the nutritional and energy content of crops. Their technology could increase production and improve profitability and sustainability across a range of important crop plants.

The Sustainable Solution Agriculture Needs

The human population continues to expand rapidly, increasing the demand for food – both for ourselves and for pets and livestock. Agricultural intensification over the last few decades has allowed farmers to increase crop yields significantly and has led to the relatively low cost of food that we enjoy today. However, intensive agricultural practices are also associated with negative environmental consequences, such as habitat destruction, soil erosion, and loss of biodiversity. Many farmers are already struggling to maintain yields as these pressures grow, let alone increase them to meet future demands.

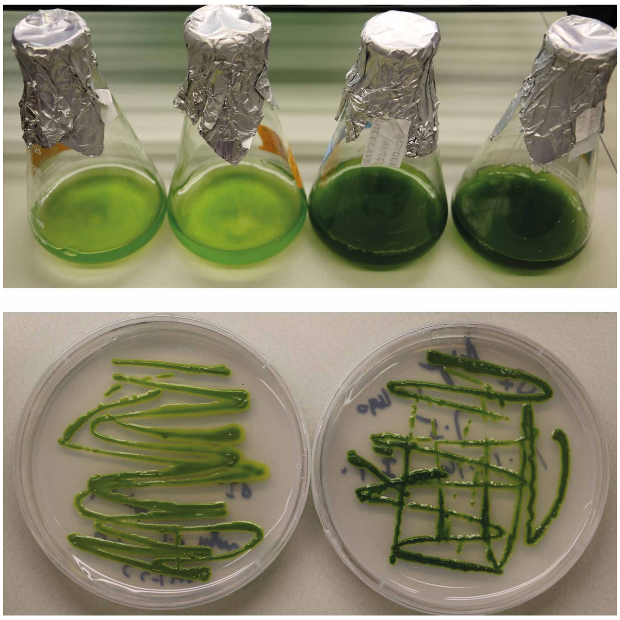
Solutions that are sustainable and environmentally friendly are urgently needed – particularly if the goal to reduce or eliminate global hunger and malnutrition is to be achieved. New tools in agriculture, ecosystem management and genetic technologies provide a suite of solutions that are sustainable, efficient, and cost-effective.

Recent advancements in genetic and molecular technologies have given scientists precise control over gene editing. Specific genes can be targeted for editing by using molecular tools with complementary DNA sequences. Genes can be altered, damaged genes can be removed, and new genes with beneficial effects can be added efficiently, and with few to zero errors. By harnessing the power of genetic technologies, scientists have created crops that are disease and pest resistant, tolerate harsh environmental conditions, and have enhanced growth rates and nutritional content.

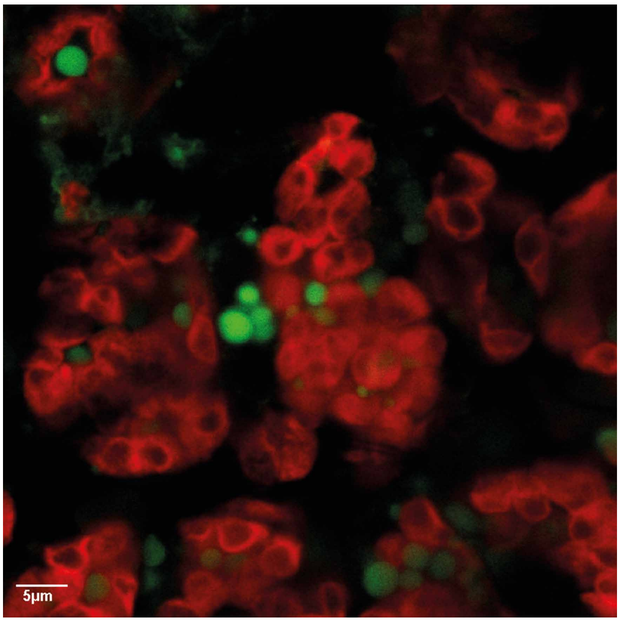
Building on years of genetic and molecular research, Dr Sanju Sanjaya, Bagyalakshmi Muthan and their colleagues from West Virginia State University and Michigan State University have developed genetic tools to improve the nutritional and energy content of crops. They increased the energy content of their genetically edited plants by targeting the mechanisms that plants use to produce energy storage compounds, the carbohydrates and 'lipids' – or fats. Healthy fats are important for heart health, cholesterol management, and overall health. Additionally, the enhanced energy content of Dr Sanjaya and his colleagues' crops could help to stave off hunger and malnutrition in vulnerable communities, particularly if combined with technologies that provide other beneficial improvements. These crops could provide environmental and economic benefits by reducing the area required to produce the same amount of energy as a traditional crop variety.

Increasing Lipid Production and Storage

Plants are the predominant 'photosynthesising' organisms on land – they capture carbon dioxide from the air and convert it into usable sugars and fats. In aquatic environments, photosynthesis is dominated by algae. From large seaweed attached to the ocean floor through to microscopic single-celled species – or 'microalgae' – drifting in the water column, algae can be found just about anywhere there is water, including ponds, rivers, lakes, and even under a dripping garden tap.



Green algae have the natural ability to synthesise and store Omega-3 fatty acids in their cells.



Expression of algal enzyme increases the production of oil droplets in plants.

Mature plants direct most of the carbon they capture into the creation of starch – a large carbohydrate that can be broken down into simple sugars and converted to energy. Starch is stored throughout the plant's 'vegetative tissues' – such as the stem, leaves, and roots – to provide an easily accessible energy source when photosynthesis is not possible. In contrast, lipids are more energy-dense than carbohydrates and take up less room for the equivalent amount of energy. The process of creating or breaking down lipids is more involved and time-consuming to achieve though, in both plants and animals. Therefore, plants tend to reserve the bulk of their lipid production and storage for places where space is at a premium – in their seeds. This is why nuts and other seeds are considered power foods – they fit a lot of energy into a small package.

Because plants can only capture a finite amount of carbon through photosynthesis, lipid and carbohydrate production are competing processes. Plants use complex metabolic pathways to partition carbon for storage compound production, which involve several enzymes and 'coenzymes' – the enzyme helpers. These pathways, and the associated enzymes, are remarkably similar in plants and algae, with the key difference being that microalgae preferentially store captured carbon as lipids. 'Many of us think Omega-3 fatty acids are made in fish and consume more fish and fish oil,' explains Dr Sanjaya. 'In reality, fish consume algae and accumulate these specialised fatty acids in their fat tissues as a reservoir.'

Through their investigations, Dr Sanjaya and his colleagues identified a group of five novel enzymes in the microalgae *Chlamydomonas reinhardtii* that regulate storage compound pathways. They used molecular tools to determine which genes are responsible for the production of these enzymes and increasing the activity of the associated metabolic pathways. They then inserted these algal genes into the genome of a model plant species, *Arabidopsis thaliana* – a flowering species related to radishes, mustard and cabbage. The genetically engineered – or 'transgenic' – plants produced the same enzymes as observed in the algae. Plants producing one of these five enzymes stored more lipids in all their tissues – not just their seeds.

Seed Oil Storage – Not Limited to Seeds

Tissue analysis revealed that the transgenic plants stored up to 6% more lipids in their vegetative tissues than the original plant lineage. So much, in fact, that globules of stored oil could be seen within the leaves under a microscope. The researchers also showed that this enhanced energy content had the expected dietary benefits. Moth caterpillars fed the transgenic plants gained more weight than caterpillars that consumed the same amount of the original plant lineage, weighing approximately a third more at the end of the feeding trial.

Analysis of the stored oil demonstrated that the lipid composition was similar to that observed in seed storage. In practice, this means that the entire plant could be used to harvest seed oils, greatly reducing the waste associated with seed oil production, and increasing efficiency and profitability.

'Enhancing the genetic control of seed development and storage compound metabolism will lead to qualitative and quantitative improvement of oilseed crops,' says Dr Sanjaya. 'With increased concentrations of seed storage compounds, these crops will help meet the global population's growing nutritional and fuel needs.'

Camelina Sativa – a promising oilseed crop.

Of the five microalgae enzymes Dr Sanjaya and his colleagues identified, only one has been characterised in the model plant species. The functions of the other four enzymes in plants are still unknown and could offer great potential in other plant species. The researchers are currently using genetic and metabolic engineering approaches to determine the enzymes' functions in storage compound regulation in plants. Dr Sanjaya suggests that understanding their function could facilitate the development of genetic technologies that alter the production and storage of different types of lipids, which vary in size and composition. These could have advantages across different applications, either as a food source, or in the production of biodiesel.

The methods for augmenting plant genomes with algal genes have been developed by Dr Sanjaya and his colleagues over years of sustained effort. Their patented process includes the method for genetically editing plant cells or tissues, growing the plant cells or tissues into a whole plant, growing the plants from seed, and harvesting the fats or oils from the mature plant.

A Technology Full of Potential

Dr Sanjaya and his colleagues are now in the process of using their technique to improve the nutritional value of the oilseed crop camelina, which is also known as false flax or wild flax. Camelina is a robust crop able to flourish on poor-quality soils, such as sandy, rocky, or nutrient-poor soils, making it ideal for cultivation where other crops would struggle. 'This energy-rich oilseed crop can grow on the marginal soil, such as reclaimed surface coal mine lands found in the USA's Appalachian regions,' says Dr Sanjaya. Energy-enhanced camelina could therefore provide nutritional benefits while also reserving prime agricultural land for other crops. In regions where poor soils are widespread, energy-enhanced camelina could provide a lifeline.

In the future, the technology could be used to increase the oil content across the vegetative tissues of a range of important crop species that produce and store oil in their seeds. Potentials include corn, soybean, potato, rice, alfalfa, and oilseed crops like sunflower or oilseed rape.

In addition to meeting food demands into the future, energy-enhanced crops are valuable for biodiesel production. Biodiesel offers a sustainable alternative to non-renewable fuels, such as petroleum. However, the crops used in biodiesel production include important food crops. Future reliance on biodiesel without implementing measures to avoid competition between food crop and biodiesel crop production could result in a rapid rise in food and fuel prices, increasing social inequality and hunger.

Energy-enhanced transgenic crops specifically designed for biodiesel production could provide a solution, by separating the cultivation for food and fuel. The higher lipid content of these crops also translates to higher biodiesel production per acre of farmland, which leaves more space for food production, development, and natural spaces.

With mounting environmental pressures and increasing demands from a growing human population, Dr Sanjaya's gene technologies could provide the sustainable solutions we need for a better future.

Meet the researchers

Dr Sanju A. Sanjaya
Energy and Environmental Science Institute
Department of Biology
Agricultural and Environmental Research
Experimental Station
West Virginia State University
Institute, WV
USA

Dr Sanju Sanjaya earned his PhD in Applied Botany from the University of Mysore, India. Upon graduating, he conducted his postdoctoral research in India, Taiwan, and the USA. Before joining West Virginia State University, he held the position of Senior Research Associate at Michigan State University. Dr Sanjaya currently holds the position of Assistant Professor of Bioenergy and Environmental Biotechnology at West Virginia State University, and Director of the university's Energy and Environmental Science Institute. His main research focus is in plant biotechnology, and designing plants and microalgae with enhanced properties, such as bioenergy and nutritional content, that improve sustainability, profitability, and production. Dr Sanjaya's research has been published in numerous prestigious journals and he holds patents for several of his gene technology inventions.

CONTACT

E: sanjaya@wvstateu.edu
W: http://www.wvstateu.edu/Faculty/Dr-Sanjaya-(1).aspx

Bagyalakshmi Muthan
Douglass Land-Grant Institute
Agricultural and Environmental Research
Experimental Station
Energy and Environmental Science Institute
West Virginia State University
Institute, WV
USA

Bagyalakshmi Muthan received her MPhil in Botany from the Bharathiar University Coimbatore, India, for a thesis entitled 'Phytochemical and antimicrobial activities of tubers and seeds of *Gloriosa superba* L'. Upon graduating, she joined Agricultural Biotechnology Research Center at Academia Sinica in Taipei, Taiwan, where her work involved genetically engineering rice, orchids, and tomatoes, after which she held a Research Associate position at Michigan State University. Muthan currently holds the position of Research Associate at West Virginia State University, Gus R. Douglass Land-Grant Institute, and Agricultural and Environmental Research Experimental Station. Her primary focus is in conducting independent research in plant biochemistry, lipids, statistics, bioinformatics, metabolic engineering and biofuels, *Agrobacterium*-mediated transformation of crops, and biotechnology.

CONTACT

E: bmuthan@wvstateu.edu

KEY COLLABORATORS

Dr Christoph Benning, Michigan State University
Dr Edgar Cahoon, University of Nebraska-Lincoln
Dr Timothy Durrett, Kansas State University
Dr Dylan Kosma, University of Nevada
Dr Abraham Koo, University of Missouri
Dr Changcheng Xu, Brookhaven National Laboratory
Dr Christian Tobias, USDA-ARS

FUNDING

United States Department of Energy
United States Air Force Office of Scientific Research
United States Department of Agriculture, 1890 Capacity Building Grant
United States Department of Agriculture, Evens-Allen Grant
National Science Foundation Research Initiation Award Grant

WEST VIRGINIA STATE UNIVERSITY 1891

COMPLEMENTING PLANT BREEDING PROGRAMS WITH BIOTECHNOLOGY

By Dr Tom Elmo Clemente, University of Nebraska-Lincoln

There are three components that impact crop harvests: the genetics of the seed sown, the environment in which the crop is grown, and the inputs employed during the growing period. For most species, the genetic component is addressed through breeding programs. Breeding programs require genetic variation within the available crop population from which parental crosses are made. Breeding programs that develop elite cultivars for commodities such as maize, soybean, wheat and sorghum, have wonderful inherent genetic diversity to utilise. However, many desired traits that breeders seek are not present within existing crop populations. It is here where the tools of biotechnology can complement plant breeding programs, by introducing novel pieces of genetic variation that can impart these favourable traits.

Genes and Proteins

Our research group resides in the George W. Beadle Center on the campus of the University of Nebraska-Lincoln. George Beadle was a geneticist who in 1958 received the Nobel Prize in physiology and medicine, along with Edward Tatum, for the 'one gene, one protein' concept.

Genes, which can be simply defined as a piece of DNA with coding information to make a protein, are first transcribed to messenger RNA (mRNA) in the nucleus of a cell. The mRNA transcript is subsequently translated to a protein in the cytosol of the cell. It is the cellular protein make-up, or so-called proteome, that ultimately gives rise to traits.

The genome sequence of soybean, for example, predicts that the species has approximately 53,000 protein encoding genes, while that of maize approximately 35,000 protein encoding genes. One of the first novel pieces of genetic variation introduced into these two crops was a gene from a bacterium that imparted tolerance to the herbicidal activity of glyphosate. Herbicide tolerance in agriculture is a desirable trait given that weed management protects crop yield. Given the source of the gene was outside of the plant species, the term 'transgene' is used. This transgene has been incorporated into soybean and maize breeding programs for over 20 years, and it remains a very powerful weed management tool for soybean and maize producers globally.

Introducing Genetic Variation

There are two requirements for successful introduction of novel genetic variation into a plant cell. The first is that a cell must be able to receive a piece of DNA, and the second is that same cell must have the capacity to become a plant that can pass the novel piece of DNA to the next generation. There are two general processes by which plant scientists deliver the novel piece of genetic variation: *Agrobacterium*-mediated delivery, and direct DNA introduction.

Agrobacterium-mediated delivery is carried out by exploiting the natural transformation capacity of the bacterium *Agrobacterium tumefaciens*. This organism causes a plant disease called 'crown gall'. The elucidation of the genetic mechanism the microbe uses to trigger the disease began in the late 1950s and the primary mechanism was identified in the late 1970s. This herculean research task was carried out primarily in several public sector research groups led by Milt Gordon, Eugene Nester, Jeff Schell, Marc Van Montagu and Mary-Dell Chilton. Dr Chilton, in my opinion, was the one that pulled it all together; she initially worked with Nester and Gordon, then moved to the Washington University in St. Louis, and then to Syngenta

Shirley Jane Sato and Tom Elmo Clemente. The two have been coordinating research activities within the Plant Transformation Core Research Facility for over 25 years at the University of Nebraska-Lincoln.

Company. The outcome of these collective activities revealed that this bacterium evolved the capacity to transfer a piece of DNA (T-DNA) from its own cell into a plant cell during the host–microbe interaction.

The process starts when this soil microbe is in the vicinity of a wounded plant; the bacterium can sense wound metabolites and proceeds to migrate towards the wound site. In the initial steps of the interaction, a series of genes are expressed. These genes serve two roles: establishing a conduit to the plant cell, known as the virB pore, and processing the T-DNA. The T-DNA is quickly coated with binding proteins that protect it and transport it through the virB pore conduit into the plant cell, ultimately integrating it within one of the host's chromosomes.

The second process by which plant scientists introduce novel bits of genetic variation into plants is direct DNA delivery, which is primarily carried out via 'microprojectile bombardment'. Like the *Agrobacterium* research outcomes, this process was developed through public sector research activities led by a scientist from Cornell University, Dr John Sanford. This process involves precipitating pieces of DNA onto microprojectile spheres composed gold or tungsten, which range in size between 0.5 and 2.5 micrometres. These DNA-coated beads are then loaded onto a film that is situated above the plant cells within a biolistic device. A vacuum is generated and the film carrying the DNA-coated beads is accelerated towards a stopping screen. Upon hitting the screen, the DNA-coated beads are delivered into the plant cell, analogous to buckshot from a shot gun.

Once the plant cells have received the DNA, either through *Agrobacterium*-mediated transformation or the direct DNA method, the cells are placed in tissue culture to initiate the regeneration process. Depending on the media formulation and culture conditions, the plant cells can follow one of two routes to transform into a whole plant: somatic embryogenesis or organogenesis. The former mirrors that of pollen fertilisation of an egg cell, while the latter will result in the differentiation of the cells into an organ, first a shoot, and the shoot subsequently induced to form roots.

Given the extremely low percentage of cells that have this dual ability to receive a piece of DNA and regenerate into a whole plant, the culturing environment must provide a selective advantage for these cells. For this reason, researchers will stack genes of interest with selectable marker genes. These genes impart the ability to grow on antibiotic or herbicide supplemented medium. Time frame from the delivery of DNA to the generation of a whole plant ranges from three to nine months, depending on the species.

Genome Editing Reagents

Plant scientists have the capacity to introduce genetic variation by the addition of a transgene, or edit a specific part of a chromosome (a locus), which can lead to either a reduction of expression of a gene or the generation of a 'null mutation', which will block the expression of a gene. These genome edits are another source of genetic variation a plant breeder can draw upon.

The ability to edit a specific genetic locus in a plant has significantly evolved over the past 15 years, the outcome being more precision. The first set of editing reagents relied upon specific proteins that can chaperone a fused molecular scissor to a genomic location. One such reagent is referred to as zinc finger nucleases. A zinc finger is a protein motif that can bind specific regions of DNA. The binding is influenced by amino acids present in the motif, and the stability of the binding

depends on a zinc ion. A motif is composed of an array of four amino acids. Each motif, depending on the array design, can recognise a specific set of three DNA base pairs. A zinc finger motif can then be assembled in a modular fashion, up to six, which will permit the recognition of a locus of 18 base pairs. The zinc finger module design is fused to a DNA scissor called *Fok1*, which was isolated from a bacterium. This fused complex is referred to as a zinc finger nuclease (ZFN). Two such ZFN reagents are delivered that specifically bind the top and bottom of the target site, which then brings the *Fok1* segments together and leads to a DNA cut (mutation).

A similar genome editing strategy was developed from knowledge about a mechanism that influences a host-microbe interaction. Many pathogens, both plant and animal, inject effector proteins into plant cells. These effectors interact with host factors, ultimately perturbing the plant's immune response in favour of pathogenicity. One class of effectors are called 'transcription activator-like' (TAL) due to their capacity to specifically bind to gene promoter regions, and activate gene transcription, which leads to mis-expression of these genes in such a way that facilitates pathogen ingress. TALs are protein modules that consist of 34 amino acid residues, varying only in the amino acids that reside at positions 12 and 13 of the module, which is called the repeat variable di-residue (RVD). The RVD dictates what part of the DNA the module will bind. Hence, one can assemble an array of modules, with altering RVDs, to bind to a specific stretch of DNA. For example, an 18-module array can be designed to preferentially bind a section of 18 base pairs.

Once the rules of TAL binding were determined, researchers used the *Fok1* fusion strategy from the ZFN editing reagent approach to develop the next genome editing tool: transcription activator-like effector nucleases (TALENs). The advantage of this approach over ZFN is more flexibility in the genome targets that can be edited.

The third generation of genome editing tools is coined 'clustered regularly interspaced short palindromic repeats', or CRISPR. This tool was developed from what researchers learned from bacterial genome sequences. In the late 1980s when performing genome sequencing of bacterial species, researchers observed an odd repetitive DNA sequence. By the early 2000s, it was realised that these repetitive DNA arrays contain segments of DNA from bacterial viruses called phages. Researchers also found repetitive clusters of DNA residing down-stream of a set of protein genes, which they termed CRISPR-associated genes (Cas).

In subsequent years, multiple research groups observed a correlation between the presence of phage DNA and the inability of that phage to subsequently infect the bacterium. This led the community to hypothesise that the Cas genes and down-stream CRISPR arrays are a type of bacterial immune system to protect against phage infections. The subsequent elucidation of this immune mechanism led to the development of CRISPR-Cas genome editing tools.

CRISPR-Cas editing reagents require a few key components: a Cas gene, and a guide RNA fused with a scaffold sequence. The scaffold sequence is what the Cas protein binds to, while the guide RNA, as the name implies, will bring the Cas protein to the genomic location targeted for editing. Regions of the genome that can be edited are dictated by a sequence referred to as the protospacer adjacent motif, which varies depending on Cas protein utilised. For example, one of the most widely used Cas proteins is Cas9, derived from the bacterial species *Streptococcus pyrogenes*, which can edit a locus where the protospacer adjacent motif is NGG, where N is any base. The guide attaches to the DNA sequence adjacent to this motif, where Cas9 will then perform an edit. Compared to the ZFN and TALEN tools, CRISPR-Cas tool use RNA to guide the molecular scissor, which gives more precision, with significantly more editable loci.

Regardless of what editing tool a plant scientist decides to use to create a targeted mutation in a genome, the reagent design must be introduced into a host cell. For this, most approaches utilise *Agrobacterium*-mediated delivery or direct DNA introduction.

Bottlenecks in Getting Novel Genetic Variation on the Market

Most traits currently on the market that were developed through the tools of biotechnology are found in the major agriculture commodities: maize, soybean and cotton. There are a few exceptions to this, for example the transgenes present in papaya and yellow squash that impart virus resistance. It is noteworthy that papaya production on the Big Island of Hawaii would not be possible without the transgene that imparts resistance to papaya ringspot virus. This has been such a resounding success story, that when the state's legislators attempted to impose restrictions on transgenic crops, papaya was exempt.

So, how can it be that these tools of biotechnology, which have been continuously improved over the past 40 years, have led to

relatively few valuable traits on the marketplace? The answer lies in the global governmental regulatory agencies that govern the movement, release and market the availability of these traits. The global regulatory agencies are not harmonised, with each country having varying sets of regulatory hurdles that must be met to obtain de-regulated status. Secondly, and more importantly, the global regulatory agencies regulate the process by which genetic variation is introduced, not the trait derived from the novel genes.

This latter point is exemplified by an output trait – a trait that directly benefits the consumer, high oleic acid soybean oil. Oil biosynthesis during soybean seed development involves a fatty acid enzyme, Fad2-1, which converts the monounsaturated fatty acid, oleic acid, into the double saturated fatty acid, linoleic acid. If genetic variation introduced into soybean leads to the blocking of Fad2-1 activity, the outcome is a soybean oil high in oleic acid (>75%) and low in polyunsaturated fatty acids. Essentially, you get an oil with similar functionality to olive oil.

Genetic variation that leads to the perturbation of Fad2-1 enzymatic activity has been introduced into soybean via three processes. The first uses a chemical mutagen, ethyl methanesulfonate. When cells are exposed to this chemical, random mutations occur in the genome, and the scientist then needs to mine the plethora of mutations to find a genetic variant of interest. The second process involves the use of the genome editing reagent TALENs, while the third employs the addition of a transgene designed to down-regulate the expression of the Fad2-1 gene during seed development.

Regarding global regulation scrutiny, ethyl methanesulfonate mutagenesis is a process that has minimal regulatory hurdles across the globe. Genome editing reagents, such as TALENs, are ever changing, and regulatory hurdles are very different from country to country. Meanwhile, for the process by which a gene is added, major regulatory barriers remain.

The regulatory landscape that must be navigated to obtain a desirable trait in a crop is a major factor that is taken under consideration during the research and development stages of a product. The cost associated with securing de-regulation status of a novel gene introduced through the tools of biotechnology can easily exceed $20 million USD. In the high oleic acid soybean example, you have the same result, a soybean oil with greater than 75% oleic acid, but achieved through different processes.

Hence, the global regulatory agencies should follow the science, wherein a strong consensus of scientists agree that the process by which we add genetic variation to a plant is safe. Instead, what is needed is regulation of the trait, not the process approach to de-regulation of traits imparted by genes introduced into plants via the tools of biotechnology.

A second issue within most global regulatory agencies is that repeated introduction of a novel gene requires regulatory hurdles to be addressed, regardless of whether the gene has been de-regulated at an earlier date. For example, as mentioned above, the first herbicide tolerance trait imparted tolerance towards glyphosate. This trait was globally de-regulated in the late 1990s and remains a very powerful weed management tool in agriculture. Now if one were to take this same transgene and re-introduce it into soybean via biotechnology, regulatory hurdles would need to be overcome in many countries, while some countries are reassessing this approach. In the USA, the regulatory governance was recently updated, and such a re-introduction of the glyphosate tolerance gene would be expedited. However, we are in a global marketplace, and a harmonised regulatory process would greatly enhance our ability to get valuable traits on the market, and importantly, into other crops beyond the major commodities.

The challenge that lies ahead is addressing the caloric needs of an increasing population, with reduced arable land for crop production. The path forward will require scientists to continue to ask questions, in the constant pursuit of knowledge, addressing both management and genetic strategies that work together in an ever-changing environment, towards ensuring a plentiful, safe and sustainable food supply for future generations. To do this will require access to all available tools, including biotechnology, to add that novel bit of genetic variation that plant breeders require to do their job.

DR TOM ELMO CLEMENTE

Eugene W. Price Distinguished Professor of Biotechnology
Department of Agronomy & Horticulture
The Beadle Center for Genetics and Biomaterials Research
University of Nebraska-Lincoln
Lincoln, NE
USA

CONTACT

E: tclemente1@unl.edu
W: https://www.unl.edu/clementelab/index.html

INTELLIGENT SPRAYING: IMPROVING PROSPECTS FOR SUSTAINABLE PESTICIDE USE

Pesticides may be essential in ensuring abundant and healthy yields of many crops, but so far, the techniques used to spray them have led to considerable environmental damage. In his research, **Dr Mark Gleason**, a plant pathologist at Iowa State University, assesses the performance of new technologies that can deploy pesticides on apple trees in more efficient and less hazardous ways. These approaches enable farmers to minimise pesticide use without sacrificing crop yields. Through combining laser-based 'LiDAR' (light detection and ranging) technology with disease-warning systems to time sprays efficiently, his project team hopes to offer more sustainable and environmentally friendly options for apple growers.

Controlling Agricultural Pests and Pathogens

No matter where in the world they live, farmers are all too familiar with the catastrophic damage that can be unleashed by pests, including insects, and pathogens such as fungi and bacteria. To safeguard the stability of food production chains while securing the livelihoods of these farmers, effective pest control is crucial.

Pesticide spraying is a widespread and long-established practice for growers of specialty crops, including apples. These chemicals are specially designed to target and disable pests and pathogens. Today, a wide variety of technologies are available to spray pesticides quickly, easily, and inexpensively over expansive areas. These technologies include so-called 'airblast' sprayers, which use fans to push sprays into canopies of perennial crops, such as apple trees, nut trees, and grape vines.

However, pesticide sprays also have unintended consequences. Since pesticides can't discriminate between harmful and non-harmful organisms, they can harm or kill innumerable organisms that benefit crops and play vital roles in the local ecosystem. To make matters worse, some pesticide spray fails to hit its target and drifts in the wind, potentially landing on farmers, farm workers and neighbours – endangering people's health and prompting lawsuits. As growers, researchers and consumers become increasingly aware of these risks, the call for more sustainable pesticide application techniques is growing urgent.

Solutions with Intelligent Spraying

The overarching problem with existing spray techniques on tree and vine crops is that they deliver pesticides across entire fields – including where there are no trees or vines. This means that off-target pesticides seep into the ground,

Fire blight. Photo by Dr George Sundin, Michigan State University.

Apple infected with Venturia inaequalis fungus.

Codling moth larvae and frass. Photo by Joachim K. Löckener, CC BY-SA 3.0 via Wikimedia Commons.

Tractor pulls a sprayer through an apple orchard in Iowa, USA. Photo by José González, Iowa State University.

where they cause pollution and can kill beneficial organisms in soil, ground water, and surface waters. Aerial drift can carry pesticide particles far beyond the boundaries of the field or farm.

Pesticides are sometimes referred to as 'cheap insurance', but pesticide sprays that fail to hit their target waste money. Remarkably, more than half of the droplets sprayed from airblast sprayers miss their targets. Alongside the significant environmental damage this can cause, inefficient use of pesticides also incurs significant costs for farmers, forcing them to spend more of their income on chemicals. Thus, the need for more precision and accuracy in pesticide spraying is urgent from many perspectives.

Agricultural engineers have begun to embrace this challenge. At the Application Technology Research Center of the USDA's Agricultural Research Service in Wooster, Ohio, Dr Heping Zhu and his technician, Adam Clark, overhauled airblast sprayers – whose technology had changed little in the past 60 years – using tools of precision agriculture. To do so, they mounted a 'laser scanning sensor' (the same LiDAR technology used in driverless cars) on the airblast sprayer.

This technology operates by firing laser beams toward the crop. The beams bounce off crop surfaces and are reflected back to a sensor. By analysing the reflections, Dr Zhu's team built up highly accurate 3D pictures of the sprayer's immediate environment – for example, a canopy of fruit trees.

As a tractor drives the sprayer between rows of trees, a computer calculates the size, density and position of the trees – thus triggering the nozzles to spray pesticides with precise timing and pinpoint direction. This automated visioning and control system makes a huge difference in spray efficiency – reducing the amount of pesticide volume needed per hectare by 30 to 70%, depending on the size and type of tree canopy – meaning much less waste and environmental hazard. Dr Zhu's Intelligent Sprayer is now available in the commercial marketplace.

But does it control insect pests and diseases as effectively as the standard airblast sprayer? Earlier field trials in a range of perennial crops – tree nurseries, raspberries and blueberries, and pecans – gave encouraging preliminary results.

But what about apples? That's where Dr Mark Gleason of Iowa State University (ISU) comes in. In a three-year project focusing on apple pest and disease management, Dr Gleason is collaborating with Dr Zhu, an Ohio State University plant pathologist, Dr Melanie Lewis Ivey, and an ISU economist, Dr Wendong Zhang. Their project expands on the spray-saving idea by combining the Intelligent Sprayer with another innovative strategy called warning systems.

Using Weather to Rate Disease Risk

The Intelligent Sprayer is a major leap forward for pesticide application because it directs spray only where it's needed, leading to far less waste per application. However, Dr Gleason and his collaborators are seeking to complement this technology, and allow farmers to make fewer sprays per season, while still protecting their fruit crops.

An apple with sooty blotch and flyspeck.

They proposed that they could achieve this by integrating a disease-warning system with the new spray technology. A warning system processes environmental information – about the weather, the pest, or the crop – to recommend spraying only when it's essential to avoid a damaging outbreak. Warning systems are a radical departure from traditional pesticide spray timing, which depends on pre-set dates rather than daily risk assessments.

Here's an example. In 2017, Gleason and his colleagues at ISU developed a warning system for an apple disease called sooty blotch and flyspeck, which causes fungal blotches on fruit. The warning system used a simple yardstick: the number of hours with a relative humidity of 90% or more since the last fungicide spray. When the total reached 385 hours, it was time for another fungicide spray. Apple growers could use this warning system to save an average of 2.3 fungicide sprays per year – a 25% reduction – compared to traditional calendar-based spray timing, with no added risk of a disease outbreak.

Combining Intelligent Sprayer and Warning System Technologies

How far can we shrink pesticide spraying without endangering an apple crop? This question drives Dr Gleason's current project. By combining the Intelligent Sprayer, which involves a lower spray volume per application, with warning systems that allow routine spraying to be avoided when disease or pest risk is low, it may be possible to maximise pesticide efficiency while minimising its risks.

In field experiments in Iowa and Ohio, Dr Gleason, Dr Ivey, and their graduate students, Olivia Meyer and Lianna Wodzicki, have been comparing this combination to each strategy by itself, and to traditional grower spray practices and equipment. The focus is on spray savings, but also on the effectiveness of disease and pest control.

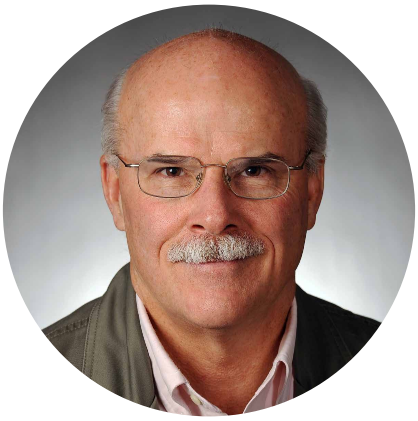
Some of the key practical questions surrounding this dual-technology project are economic ones. For example, under what type of orchard scenario would an Intelligent Sprayer be profitable, and how soon would a grower recover the cost outlay? How would warning systems impact profitability?

Dr Zhang and his graduate student Nieyan Cheng are currently putting together an economic analysis to help apple growers evaluate whether they want to adopt the new strategies. An Advisory Panel of commercial apple growers from Iowa and Ohio meet regularly with Dr Gleason's project team to keep the project grounded, and the team, led by ISU Research Associate José González, is sharing the results with growers throughout the Midwest via podcasts, blog posts, videos, a website, and field days.

Transforming Pesticide Application

In the coming decades, unprecedented changes to the Earth's climate and ecosystems will present farmers worldwide with many new risks. Dr Gleason's project addresses these challenges by applying technology to minimise the health and environment risks caused by off-target and unnecessary pesticide spraying, and to safeguard growers' profits.

Beyond apples, the project's findings could be relevant to many other key food crops that currently receive high pesticide loads, thereby paying dividends for food security, environmental quality, and agricultural sustainability.



Meet the researcher

Dr Mark Gleason
Department of Plant Pathology and Microbiology
Iowa State University
Ames, IA
USA

Dr Mark Gleason holds two PhD degrees – the first in Environmental Sciences from the University of Virginia, and the second in Plant Pathology from the University of Kentucky in 1985. Now a Professor in the Department of Plant Pathology and Microbiology at Iowa State University, he specialises in research on several major fruit and vegetable crop diseases. The scope of his research covers the genetics and evolutionary biology of these pathogens, and is also leading to new ways to detect, manage, and prevent them. Dr Gleason also teaches a broad range of university courses, on topics including Integrated Pest Management, ecologically based pest management, tropical agriculture, turfgrass disease management, research ethics, and professional speaking skills. He has published more than 200 research papers, and has received several awards for his important work, including the Outstanding Achievement in International Agriculture at Iowa State University in 2012.

CONTACT

E: mgleason@iastate.edu
W: https://www.plantpath.iastate.edu/people/mark-gleason
W: https://www.smartapplespray.plantpath.iastate.edu/

IOWA STATE UNIVERSITY

KEY COLLABORATORS

Melanie Lewis Ivey and Lianna Wodzicki, The Ohio State University
Heping Zhu and Adam Clark, USDA-ARS
José González, Wendong Zhang, Olivia Meyer, and Nieyan Cheng, Iowa State University

FUNDING

Crop Protection and Pest Management Program, USDA NIFA

FURTHER READING

L Chen, M Wallhead, M Reding, L Horst, H Zhu, Control of insect pests and diseases in an Ohio fruit farm with a laser-guided intelligent sprayer, HortTechnology, 2020, 30, 168.

L Chen, M Wallhead, H Zhu, A Fulcher, Control of insects and diseases with intelligent variable-rate sprayers in ornamental nurseries, Journal of Environmental Horticulture, 2019, 37, 90.

H Rosli, DA Mayfield, JC Batzer, PM Dixon, W Zhang, ML Gleason, Evaluating the performance of a relative humidity-based warning system for sooty blotch and flyspeck in Iowa, Plant Disease, 2017, 101, 1721.

H Zhu, R Rosetta, ME Reding, RH Zondag, CM Ranger, L Canas, A Fulcher, RC Derksen, HE Ozkan, CR Krause, Validation of a laser-guided variable-rate sprayer for managing insects in ornamental nurseries, Transactions of the ASABE, 2017, 60, 337.

FIGHTING FIRE BLIGHT IN ORGANIC ORCHARDS

The bacteria that causes fire blight in apple and pear trees is notoriously difficult to control without antibiotics. With new regulations in the US preventing antibiotic use in organic orchards after 2014, organic farmers faced an impossible choice – lose their organic certification or risk the death of their trees. Working against the clock, plant pathologist **Dr Kenneth Johnson** from Oregon State University accelerated his efforts to provide organic farmers with another option. With his team of researchers and outreach specialists, he developed and evaluated non-antibiotic management strategies for fire blight in organic apple and pear orchards.

An Organic Apple and Pear Production Crisis

Apples and pears are so loved the world over that some of the thousands of varieties have become household names. Whether it's the crisp, refreshing flavour of a 'Granny Smith' apple, or the smooth sweetness of a 'Bartlett' pear, there is a flavour to suit every palate. And how different the world would be without warm apple pies, or a refreshing cider on a hot summer day.

Apple and pear cultivation is a huge global industry. In Europe, apples and pears are the most consumed fresh fruit, while in the US they are second only to bananas. In recent decades, consumer demand for organic produce has increased remarkably. In 2017, production of fresh organic apples and pears was worth around $600 million to western US growers and packers. In Washington State alone, 28,500 acres of apple and 3,200 acres of pear orchards are organic.

Unfortunately for apple and pear producers, insect pests, fungi and bacteria pose great threats to fruit production. Pests and diseases that damage the appearance of the fruit dramatically reduce their market value. This damage is relatively mild, however, in comparison to the damage wrought by diseases such as fire blight.

Caused by a pathogenic bacterium – *Erwinia amylovora* – fire blight ruins flowers and fruit before progressively killing off twigs, branches, and eventually the entire tree. Even small outbreaks of fire blight can incur large yield losses. For example, 10% fire blight infection that has spread to the roots of a four-year-old apple orchard can result in losses of around $12,000–15,000 per acre.

Antibiotics have been indispensable in controlling the devastating disease and have safeguarded the livelihoods of thousands of apple and pear producers in the process. The current production system for apples and pears was built on the high yields that were only possible with this effective tool against fire blight. Until recently, organic certified orchards were permitted to use antibiotic treatments to control fire blight. In 2012, however, the National

Severe fire blight epidemic in central Washington. CREDIT: Tim Smith, WSU.

Organic Standards Board voted to remove the antibiotics – oxytetracycline and streptomycin – from the National Organic Program's list of allowable substances after 2014.

Organic producers' options were limited. Varieties with resistance to fire blight were, and still are, years away from reaching producers. So, either these growers had to give up their organic certification – and lose their niche marketability – or they risked the disaster of a fire blight outbreak.

Classic 'Shepard's crook' symptom of fire blight. CREDIT: Tianna DuPont, WSU.

Fortunately, Dr Kenneth Johnson from the Department of Botany and Plant Pathology at Oregon State University had been investigating non-antibiotic control strategies for fire blight. Suddenly, however, he had a race against the clock to evaluate and share non-antibiotic fire blight control strategies with organic producers. Along with his team of researchers at Oregon State University and Washington State University, Dr Johnson refined a treatment regime against the fire blight bacteria using organic-permitted compounds and a yeast with biological control properties.

Fire Blight Infections

The fire blight bacterium is native to eastern North America, but since the mid-1900s has spread to regions across the world. In western US, infections commonly occur in May and June on the second flush of flowers, but occasionally, infections can wreak havoc during the primary bloom.

Pears are especially susceptible to fire blight. Since fire blight spreads faster in warm, wet environments, the susceptibility of pears has limited their production to semi-arid regions. Although less susceptible than pears, apple production is at increasing risk of serious economic damage because of the high density of trees grown in intensive orchard systems and high consumer demand for fruit of susceptible varieties.

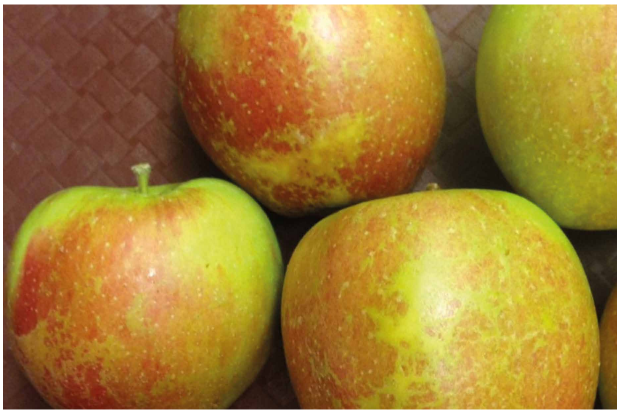
Examining the life cycle of fire blight provided Dr Johnson with the clues he needed to solve the problem of controlling the disease without antibiotics. The bacteria survive the winter months in diseased patches – called 'cankers' – under the tree bark. During humid periods in the spring, the bacteria begin to ooze out of the edges of cankers, attracting hungry insects that use this ooze as a food source – and consequently spread the disease. A single drop of canker ooze can contain between 100 million and one billion fire blight bacteria!

Insects and rain transfer the bacteria from old cankers to new flowers, where they multiply rapidly, and later between infested flowers. In wet weather, the bacteria are washed into the nectar-producing region of the flower, where they enter the tree's vascular system. The bacteria move through the tree, killing tissues as the infection spreads. Twigs on infected trees develop a characteristic charred appearance – hence the name 'fire blight'. Fire blight infections spread rapidly through young tissues, making young trees particularly vulnerable – and western US growers have been planting a lot of young apple trees.

The later-season secondary flush of flowers, common in some varieties of apple and pear, are at especially high risk of fire blight infection because warmer air temperatures promote bacterial growth, and fire blight pressure in the orchard is usually higher than earlier in the season. 'Bartlett' pear and 'Pink Lady' apple varieties, for example, often produce abundant secondary flowers. 'Heat drives the build-up of the pathogen population on flowers, and moisture triggers the infection event,' explains Dr Johnson.

'Frequently, when a period of high temperature without rain occurs, new infections are limited to low areas in the orchard, where dew is more likely to occur. As few as two hours of wetting by dew is sufficient to trigger infection if the

Ooze droplet of the fire blight pathogen. CREDIT: Tianna DuPont, WSU.



Russeting on Braeburn apple caused by Aureobasidium pullulans. CREDIT: Ken Johnson.

temperatures preceding the wetting event were favourable for pathogen growth,' he says.

An Organic Solution

With no single non-antibiotic substance offering the same level of control of fire blight as antibiotics, Dr Johnson's challenge was to evaluate the properties of each available alternative, determine the appropriate timing for application based on the disease life cycle, and develop an integrated and sequenced application protocol. His research revealed that organic producers must follow a season-long program that includes application of copper sprays, lime sulphur sprays, and 'Blossom Protect' – a treatment containing the yeast *Aureobasidium pullulans*. 'By integrating multiple preventative materials, we are able to target the pathogen at each stage of its life cycle and gain overall better control,' he says.

Conventional producers rely on weather and fire blight risk models to determine their antibiotic treatment regime from year to year. But because alternative treatments are not as effective, Dr Johnson recommends organic growers take a more risk-averse approach. 'In organic programs, where biological materials are important components, spray applications based only on the model warnings will likely be too late to achieve effective control,' he explains. 'In order to be competitive, biologicals need to grow their populations on the flowers before fire blight pathogen cells arrive.'

Dr Johnson recommends treating each tree with Blossom Protect during the early blooming stages, to maximise the abundance of the beneficial yeast. Additionally, he suggests that organic growers extend their fire blight management programs longer than they may think is necessary. During some of his field trials in Oregon, he discovered an alarming increase in the number of fire blight bacteria after the flowers had already dropped all their petals. In just one week, the number of bacteria had increased from 200 cells to over one million cells in a single flower. Growers ceasing fire blight control measures too early could be risking a devastating surprise outbreak.

Various strains of the yeast *Aureobasidium pullulans* have been shown to be effective against fungal fruit rot diseases. However, only two known strains – those in Blossom Protect – are effective against fire blight. These two strains are remarkably superior to any other yeasts offering biological control properties against the bacteria. Interestingly though, Dr Johnson demonstrated that Blossom Protect did not prevent fire blight bacteria from multiplying on the flowers. Thus, the yeast prevents fire blight infection through another mechanism – which is still a mystery to scientists.

Blossom Protect was developed in Germany and was adopted in the western US shortly after, where it is used extensively. The treatment never gained widespread use in more humid Europe, however, owing to the yeast's propensity to cause 'russeting' – the roughened, brown discolouration of apple and pear skins. Although russeting is cosmetic, the damage lowers the marketability of the fruit.

Russeting results when sprayed materials interact with moisture on the fruit surface in the month following flowering, and as such, late spring rains in northern Europe and the eastern US increases its frequency. In arid growing regions, such as central Washington, russeting caused by the yeast is rare. Growers in wetter regions, especially those growing more susceptible smooth-skinned pear varieties, may have to make a difficult decision about whether fire blight or russeting poses a greater risk.

Dr Johnson and his team have been sharing their non-antibiotic fire blight control strategy with organic growers through a series of webinars, publications, and presentations. They have shared their research at both national and international conferences. Future research could provide additional non-antibiotic substances to control fire blight, and ultimately, fire blight resistant varieties may become increasingly popular when they reach producers. But for now, Dr Johnson has provided effective tools for organic growers to maintain their apple and pear yields, retain their organic certification, and safeguard their livelihoods.

Meet the researcher

Dr Kenneth B. Johnson
Department of Botany and Plant Pathology
Oregon State University
Corvallis, OR
USA

Dr Kenneth B. Johnson earned his PhD in Plant Pathology from the University of Minnesota. In 1988, he began his teaching and research career at Oregon State University, where he currently holds the position of Professor of Botany and Plant Pathology. His research focus is understanding how variability in environment and host and pathogen populations affect the development of plant disease. Dr Johnson's research has contributed to the development of integrated disease control strategies of fruit and vegetable crops. He is committed to sharing his findings both nationally and internationally, presenting at multiple horticultural and agricultural meetings each year. In addition to his research, Dr Johnson lectures across a range of plant pathology modules, supervises research students, and has been an editor of multiple peer-reviewed journals.

CONTACT

E: Kenneth.Johnson@oregonstate.edu
W: https://scholar.google.com/citations?user=zqpYIIoAAAAJ&hl=en

Oregon State University

KEY COLLABORATORS

Timothy Smith, David Granatstein and Tianna DuPont, Washington State University Extension Service
Rachel B. Elkins, University of California Agriculture and Natural Resources
Todd N. Temple, Oregon State University

FUNDING

US Department of Agriculture - National Institute of Food and Agriculture (USDA-NIFA)
Washington Tree Fruit Research Commission
USA Pear

FURTHER READING

TN Temple, EC Thompson, S Uppala, D Granatstein, KB Johnson, Floral Colonization Dynamics and Specificity of *Aureobasidium pullulans* Strains Used to Suppress Fire Blight of Pome Fruit, Plant disease, 2020, 104, 121. https://doi.org/10.1094/PDIS-09-18-1512-RE

KB Johnson, TN Temple, Evaluation of strategies for fire blight control in organic pome fruit without antibiotics, Plant disease, 2013, 97, 402. https://doi.org/10.1094/PDIS-07-12-0638-RE

INTEGRATING SUSTAINABILITY WITH PRODUCTIVITY IN CROP AND ANIMAL FARMING

The demand on agricultural systems to increase the food supply has risen sharply as the global population continues to grow. However, as agricultural systems increase productivity, they also emit more greenhouse gases and exacerbate climate change. Simultaneously meeting food supply demands and reducing environmental impact in agricultural settings is one of the most important issues of our time. **Dr Marília Chiavegato** of The Ohio State University has dedicated her career to studying the ecological components of agricultural ecosystems, called 'agroecosystems'. Her team's findings will aid the development of management practices that not only boost productivity, but also lower the environmental impact associated with conventional agriculture.

Agroecosystem Management

Simultaneously addressing the global food crisis and climate change requires that we look at agroecosystems through a new lens. Though agricultural settings are human-made, they are still complex and dynamic ecosystems. Thus, just as in natural systems, all components of the ecosystem such as the soil structure, plant diversity and animal populations, interact with one another to modify the landscape and any associated ecological services.

These components can have a large influence on agricultural output, such as livestock meat yields, and significant environmental impacts, such as the amount of greenhouse gas emissions. Moreover, there are social, political, and economic considerations that influence agroecosystems that are typically not encountered in natural ecosystems.

Additionally, climate change will undoubtedly impact agricultural settings, reducing our ability to grow food, and forcing us to change how we manage land. An increase in flooding, drought and depleted soil all need to be considered when planning for the future. Therefore, it is important that agroecosystems are resilient to the shocks and stressors of a changing climate, while also maintaining high levels of productivity. Prior to making land management decisions, we must increase our knowledge of the mechanisms underpinning agroecosystems, and how these might change with a warming planet.

Dr Marília Chiavegato and her lab at The Ohio State University have used methods based on a systems approach, in which management strategies are monitored on farms rather than simulated, to begin to tackle these important questions and address prominent knowledge

gaps. Dr Chiavegato's team aims to better understand how the interaction of ecological factors, such as plant root structure and soil quality, ultimately affect farm productivity and environmental impacts. In doing so, we can better design sustainable and effective management strategies that promote resiliency and productivity in agroecosystems.

In their recent work, Dr Chiavegato and her colleagues have used

multidisciplinary methods to track both greenhouse gas emissions and ecological aspects of agroecosystems managed using different strategies. By teasing apart the mechanisms underpinning agroecosystems, Dr Chiavegato's work contributes both to ecological theory and to applied management practices. Her recent work focuses on flood-prone systems in the midwestern region of the USA and grasslands in the tropics.

Flooding in Agroecosystems

A significant amount of land grazed by cattle and sheep is prone to flooding. For example, In the midwestern US, flood-prone grazed lands contain productive forage for cattle, and provide ecosystem services such as trapping sediment, providing habitat, and storing carbon in the flooded soil and roots of the plants.

However, despite the fact that they are ubiquitous and important agroecosystems, flood-prone regions are generally managed in the same way as areas that are not prone to flooding. Given the fact that floods can change the plant composition of an area and modify the soil chemistry and microbiology, these areas require specific management strategies compared to lands that do not experience these changes.

Improved and specific strategies are particularly needed in flood-prone areas that are grazed, as we still do not understand how flooding and grazing can interact and affect one another. Additionally, in many areas, climate change is expected to increase the amount of intense rainfall events. Thus, not only are increased flood events more likely, they will also be more severe, increasing the prevalence of these areas.

To address this knowledge gap, Dr Chiavegato and her colleagues are creating a framework to understand how a series of flooding events will initiate a series of changes in an agroecosystem's ecological pools, such as the soil or plant life. The framework will then track how these changes will interact to modify farm output, such as the quality of forage and meat, and environmental outputs, including greenhouse gas emissions.

To provide data to build the framework, the team will monitor greenhouse gas emissions, forage quality, organic matter content, and other important variables in flood-prone and non-flood-prone grazed pastures in Southern and Northern Ohio. Ultimately, the aim of the work is to understand the effects of recurring flooding on the quality of the air, soil and forage. This understanding will allow the team to develop strategic grazing management options to increase the productivity and sustainability of these areas for current and future conditions.

This project also represents an overarching theme of Dr Chiavegato's: the importance of increasing our knowledge of the structure and behaviour of agroecosystems before recommending management strategies.

Sustainable Intensification

Sustainable intensification describes the process of increasing agricultural yields through methods that reduce adverse environmental impacts, such habitat destruction and greenhouse gas emissions. For example, in dairy farm systems, there has been an effort to increase the quality and quantity of milk produced while simultaneously reducing the amount of methane, a potent greenhouse gas, that is emitted from the digestive systems of cattle. Such research requires that cattle and the grass they graze are studied synchronously.

To optimise light capture, grasses first increase their leaf surface area, and finally, elongate their stem to reach maximum vertical growth. However, typically, the stems of the grass are less digestible for cattle than are their leaves.

In a recent study, Dr Chiavegato and her colleagues hypothesised that grass that is not allowed to reach the final stage of stem elongation will not only provide more nutritious forage for the cattle, but will also be more digestible and reduce cattle methane emissions. Thus, grazing strategies that manage grass height has the potential to provide cattle with more nutrient-rich forage, reducing their methane emissions and potentially improving the quality of their milk.

To test their hypothesis, the researchers implement mowing treatments on elephant grass pastures in Brazil. They then allowed the cattle to graze on treated plots, while other cattle grazed on control plots in which the grass was not manipulated. In plots that were managed, cows emitted 21% less methane per kilogram of milk they produced, and the milk yield increased by a whopping 51%. Thus, the team found that this strategic grazing management was successful in optimising the output of the farm, while also reducing greenhouse gas emissions.

Cattle Density and Greenhouse Gas Emissions

Optimising sustainable grassland management requires that we not only focus on the characteristics of the grass, but also those of the grazed animals. The number of cattle on a farm, known as stocking, is an important and easily manipulated variable in agricultural management. Stocking density, which describes the number of cattle per area of land, and the number of times cattle are moved per day have been linked to the amount of greenhouse gas emissions from grassland ecosystems.

To compare the effects of cattle management on greenhouse gas emissions, Dr Chiavegato and colleagues from Michigan State University monitored the movement of three greenhouse gases – carbon dioxide, nitrous oxide and methane – through two different systems that had different cattle stocking densities. The researchers also monitored ecological variables, including soil organic matter and nitrogen content, to test the hypothesis that fewer cattle per hectare would lead to reduced greenhouse gas emissions.

'We looked at multiple sources of greenhouse gas emissions (soil and animal) and multiple gases simultaneously,' says Dr Chiavegato. 'There were trade-offs between sources and gases,

in a way that in the end, no differences were found between the systems. This holistic view is unique to our study.'

However, they did not account for carbon sequestration into the soil. In this situation, greenhouse gases could be captured from the atmosphere, converted into organic matter and stored in the soil, offsetting the emissions released from the farm. Thus, the study highlighted the need for incorporating the capture and storage of greenhouse gases into our models for farm emissions. These types of studies are instrumental in illustrating which variables we still need to study more before we can quantify, and thereby manage, the environmental impact of agroecosystems.

Striking the Right Balance

The seemingly paradoxical situation of increasing agricultural productivity while reducing the environmental impact of agriculture is an urgent and complex global problem. Its solution, however, first requires that we study agroecosystems as ecological systems with a variety of interacting components.

Increased knowledge of these systems will also allow us to better predict how they may react to weather pattern changes that are undoubtedly being brought on by climate change. Dr Chiavegato has dedicated her career to unravelling these complex interactions with the applied goal of designing sustainable management strategies for a variety of agricultural settings. Her foundational work has already led to management strategies that decrease the footprint of agroecosystems and increase their productivity – a difficult, yet crucial, balance to strike.

Meet the researcher

Dr Marília B. Chiavegato
Department of Horticulture and Crop Science
Department of Animal Sciences
The Ohio State University
Columbus, OH
USA

Dr Marília Chiavegato started her academic career in Brazil, where she received an MS in Applied Chemistry, with a focus on agriculture and the environment, at the University of São Paulo. In 2014, she graduated with her PhD in Animal Science from Michigan State University. After returning to Brazil for a postdoctoral position at her alma mater, she began her current position as an Assistant Professor at The Ohio State University in the Department of Horticulture and Crop Science, with a joint appointment in the Department of Animal Science. An overarching theme of Dr Chiavegato's work is to improve the ecological sustainability of agricultural systems without sacrificing farm output. Through her systems-approach research, in which different aspects of an agricultural ecosystem are monitored, she aims to design effective agricultural land-management strategies. She has advised undergraduate, masters, and doctoral students and has a robust publication profile commensurate with her contributions to the field.

CONTACT

E: chiavegato.1@osu.edu
W: https://hcs.osu.edu/our-people/marília-chiavegato

KEY COLLABORATORS

Dr Doug Jackson-Smith, The Ohio State University
Dr Anthony J. Parker, The Ohio State University
Dr Mark Sulc, The Ohio State University
Dr Jason Rowntree, Michigan State University
Dr Steve Lyon, The Ohio State University

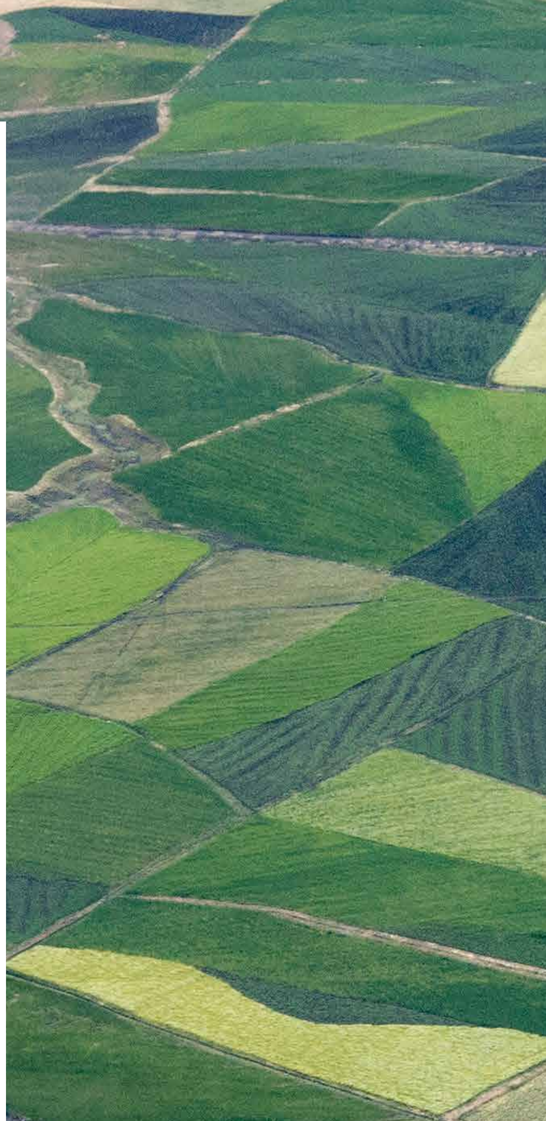
FURTHER READING

GFS Congio, CDA Batalha, MB Chiavegato, A Berdnt, PPA Oliveira, RTS Frighetto, TMR Maxwell, P Gregorini, SC Da Silva, Strategic grazing management towards sustainable intensification at tropical pasture-based dairy systems, Science of the Total Environment, 2018, 636, 872.

MB Chiavegato, JE Rowntree, WJ Powers, Carbon flux assessment in cow-calf grazing systems, Journal of Animal Science, 2015, 93, 4189.

THE OHIO STATE UNIVERSITY

NASA HARVEST: MONITORING FOOD SECURITY FROM SPACE DURING THE COVID-19 PANDEMIC



In the face of the combined challenges of climate change and COVID-19, reliable access to accurate information about crop health has never been more crucial. **Dr Michael Humber** at the University of Maryland is the Data Lead of the NASA Harvest project – a global collaboration of researchers from many different backgrounds, who are aiming to provide this data using advanced satellite-based technologies. His team's work has already had an important impact on systems that warn farmers of likely crop failures before they occur, and could be vital for ensuring global food security in the coming decades.

Achieving Food Security

Despite decades of progress towards improving food security for the global population, the recent trend in declining world hunger appears to be slowing down. In 2017, the number of undernourished people increased for the third year in a row to reach over 820 million – a statistic that now threatens the ambitious United Nations goal to eradicate world hunger by 2030.

Among the main drivers of this worrying observation is an increase in extreme weather, widely attributed to climate change. As global temperatures rise, events including droughts, floods, and storms are increasingly coming to damage and destroy crops, particularly in the developing world.

On top of this threat, the COVID-19 pandemic has made the future of global food security even more uncertain. Because of the increased costs of labour created by travel restrictions, many farmers have made the difficult decision that their crops would be more expensive to harvest than to leave in the ground. With communities in many developing nations relying heavily on exports of these crops, the risk of reversing the previous trend in world hunger is now at its highest in decades. Clearly, such an all-encompassing problem requires coordinated and highly advanced solutions.

A Need for Early Warning Systems

Ultimately, there are two key aspects to the challenges faced in tackling these issues. In the developing world, crops are generally far more vulnerable to failure, due to lower-yielding crop varieties, limited access to seeds and fertiliser, and a lack of reliable irrigation infrastructure. Because of this, farmers are far less able to protect their crops during extreme weather events or economic disruption.

In addition, many nations don't rely on the crops they grow themselves to sustain their populations, but instead rely on imports. One particularly clear example is Egypt – which has a large, dense population, but very little arable land suitable for growing wheat. As a result, the country is the world's largest importer of the crop – sourcing most of it from Russia, where wheat supplies are abundant. Similar supply chains are now widely used in both poorer and developed countries, meaning crop failures can have severe knock-on effects across the globe.

To fully understand the combined impacts of climate change and COVID-19 on global food security, it is critical for agricultural stakeholders to accurately assess levels of crop damage, well before they are harvested. Furthermore, these assessments must take place across a wide range of scales – from regions where communities depend on locally-produced crops, to entire nations, which depend on

international supply chains. If achieved, advanced early warning systems would give these populations critical time to prepare for oncoming food shortages. Currently, however, the human and technological networks required for such high-quality monitoring are not being widely applied.

Monitoring Crops from Space

So far, early warning systems have widely relied on ground-based methods for monitoring crops, including information taken directly from farmers and field surveyors, combined with weather models to estimate the likely impacts of weather on food production. Although this data can be crucially important, efforts to collect it must be carried out by many different institutions and organisations, from regional to international scales. Naturally, it is incredibly challenging to then coordinate this data, enabling relevant communities to be informed about future food shortages.

This challenge has been exacerbated by the COVID-19 pandemic, which has limited the ability of organisations around the world to conduct field operations. As a result, remote sensing has emerged as a highly effective method for observing and forecasting crop production. From space, these instruments can monitor a wide variety of factors – on scales ranging from several centimetres to thousands of kilometres.

From their visualisations alone, satellites can determine how green a patch of land is, due to the density of vegetation growing there. In addition, they can monitor weather, soil moisture, and the amount of water being evaporated from leaves – all of which are relevant to crop health.

These measurements are now benefiting from a growing number of space-based satellites, with sensor resolutions high enough to assess differences in crop quality between different parts of the same field. By coordinating these observations with ground-based measurements, early warning systems could soon improve rapidly. Dr Michael Humber at the University of Maryland and his colleagues play a key role in supporting these efforts.

Launching GEOGLAM

In 2011, heads of state from the G20 forum endorsed the launch of the Group on Earth Observations Global Agricultural Monitoring (GEOGLAM) initiative. Today, GEOGLAM aims to provide widely accessible transparency for assessments of global food markets, enabling nations and communities to better coordinate their activities during food shortages created by crop failures.

To support the objectives of GEOGLAM, NASA launched the NASA Harvest program – an international collaboration including researchers and international stakeholders from over 50 institutions worldwide, whose collective efforts are led by Dr Inbal Becker-Reshef, Director of the NASA Harvest Program and Associate Research Professor at the University of Maryland.

By taking data from space-based satellites, and analysing them using the latest available techniques, these researchers are now taking important steps towards improving global food security in the coming decades. Since 2013, the team has coordinated monthly assessments of the health of four staple

crops, including wheat, rice, maize and soy, within many of the world's most important agricultural regions to achieve an international consensus on monthly crop conditions. Many of Dr Humber's colleagues have now gone on to apply their gathered data in a variety of innovative projects.

Successes so Far

One of these projects, led by Dr Humber's colleague Dr Hannah Kerner, focused on cropland mapping in Togo, West Africa. Using NASA Harvest satellite imagery alongside poverty and census data, the team created a system that can rapidly identify priority areas. This system allows the Togolese Government to protect farmers from shocks triggered by the COVID-19 pandemic that could negatively impact the country's food security.

In another recent project, Dr Mehdi Hosseini from the University of Maryland developed an approach that can quickly assess crop damage over vast regions spanning millions of acres. In August of 2020, a series of windstorms, known as a 'derecho', caused widespread damage to about one-third of soybean and corn crops in the state of Iowa. The NASA Harvest researchers combined different types of satellite data to develop maps that show the overall damage caused for each crop type. The team's approach to identifying damaged areas and assessing the extent of the damage is critical to enabling government agencies and insurance companies to rapidly respond to the disaster, even in the midst of the pandemic.

A final example is a study led by Dr Catherine Nakalembe, head of the African Program for NASA Harvest. Using satellite observations, her team identified the early stages of a drought in Uganda in 2017. This information was used by government agencies to act proactively to an impending production shortfall rather than acting reactively to a food crisis. Since then, these systems have been used to inform farmers and local governments that crop yields are likely to be lower in the near future – giving them crucial time to prepare for potential threats to food security.

Continuing Measurements During COVID-19

This work comes at a particularly critical time, as travel restrictions imposed by COVID-19 have made it extremely difficult for researchers to gather data on the ground. At the same time, the pandemic is causing significant disruption to global chains of supply and demand for food. This threatens to impact global food security in the near future, with impacts felt most strongly in the developing world.

In their latest research, Dr Humber's team is working towards expanding the scope of the NASA Harvest project to study these effects in detail, even without access to reliable ground-based measurements.

The team's results are now filling in potentially dangerous gaps in this data, enabling farmers, governments, and agricultural stakeholders to continue to accurately monitor the health of their crops. Their observations can also be combined with other data, including estimates of market prices, freight costs, and numbers of daily new COVID-19 cases and vaccinations, enabling more detailed assessments of the impacts of the pandemic. As the economic effects of COVID-19 are likely to be felt for years to come, the project could become a crucial tool ensuring sustainable global recovery.

Preparing for New Challenges

The ultimate goal of Dr Humber's team is to build a 'dashboard' of data – bringing information about supply chains, ground-based crop assessments, and satellite observations, together in one place. Combined with the COVID-19 data gathered by John Hopkins University, their interactive tool will enable all players involved in agriculture, food production, and supply chains to easily access the information they need to coordinate their efforts, and make the best possible decisions.

With these measures in place, the dashboard could one day enable these groups to prepare for potential future incidents, including pandemics, human conflicts, natural disasters, or any other event with the potential to cause major disruption to the global economy. Even as the effects of the pandemic subside in the coming years, climate change threatens to place an ever-increasing strain on food security. NASA Harvest's investment in documenting supply chains will enable analysts to learn from the past in order to begin to understand how future shocks might affect the flow of agricultural goods and food availability in the future.

To avoid a reversal in the previous trend of declining world hunger, intelligent decisions will be more important than ever. As a result, the team's work could play a vital role in continuing the United Nations' goal to eradicate world hunger, even in the face of mounting challenges.

Meet the researcher

Dr Michael L. Humber

Department of Geographical Sciences

University of Maryland

College Park, MD

USA

Dr Michael Humber completed his PhD in Geographical Sciences at the University of Maryland in 2019. Since 2015, he has been the NASA Harvest Data Lead at the University of Maryland's Department of Geographical Sciences. This important role involves collaboration with groups within agriculture, government, and the private sector to create customised software, capable of meeting the unique monitoring needs of individual organisations. Elsewhere, Dr Humber's research interests include the use of high-performance computing for image analysis; assessments of the quality and accuracy of maps based on satellite observations; and methods for mapping crops and agricultural practices at national scales.

CONTACT

E: mhumber@umd.edu

W: https://geog.umd.edu/facultyprofile/humber/michael

KEY COLLABORATORS

Inbal Becker-Reshef, Co-Principal Investigator, UMD/NASA Harvest
Estefania Puricelli, Co-Investigator, UMD/NASA Harvest
Antonio Sanchez-Galvez, UMD/NASA Harvest
Christina Justice, UMD/NASA Harvest
Blake Munshell, UMD/NASA Harvest
Jack O'Bannon, UMD/NASA Harvest
John Keniston, UMD/NASA Harvest
Mary Mitkish, UMD/NASA Harvest
Dan O'Neill, Geospatial Research Laboratory, US Army Corps of Engineers
Soonho Kim, IFPRI

FUNDING

NASA

FURTHER READING

I Becker-Reshef, C Justice, B Barker, M Humber, F Rembold, R Bonifacio, M Zappacosta, M Budde, T Magadzire, C Shitote, J Pound, Strengthening agricultural decisions in countries at risk of food insecurity: The GEOGLAM Crop Monitor for Early Warning, Remote Sensing of Environment, 2020, 237, 111553.

I Becker-Reshef, B Barker, M Humber, E Puricelli, A Sanchez, R Sahajpal, K McGaughey, C Justice, B Baruth, B Wu, A Prakash, The GEOGLAM crop monitor for AMIS: Assessing crop conditions in the context of global markets, Global Food Security, 2019, 23, 173.

DEVELOPING FOOD PROCESSING METHODS THROUGH SCIENTIFIC AND ENGINEERING SOLUTIONS

The food processing industry generates enormous quantities of waste every year. On top of this, the way that food is processed can have negative impacts on the health of consumers. Therefore, it is vitally important to develop new food processing methods that consider human health while producing minimal waste. **Dr Vijaya Raghavan** and his research group at McGill University, Montreal, have been applying their expertise in chemistry and engineering to develop and optimise food processing techniques, to ensure the future health of people and the environment.

Food Processing

Today, almost all of the food we consume has been processed in some way. Food processing methods offer a range of important benefits, such as extending shelf life, and providing foods that are more palatable or edible than their unprocessed counterparts.

For instance, the various processing steps involved in converting wheat crops into loaves of bread – from harvesting and milling, to kneading and baking – unlock the nutrition contained within the raw grain, converting it into an edible form. Additionally, fish processing often involves gutting, deboning and washing, to obtain fresh meat that can be either transformed into safe and palatable products, or frozen or smoked to preserve the meat for months, or even years. Such preservation techniques allow consumers to enjoy fish well beyond the harvest season and far from where the fish were caught.

Without food processing, the needs of urban populations would be difficult to fulfil, and our selection of foods would be extremely limited, particularly in winter. However, certain aspects of food processing raise concerns over both environmental sustainability and the health of consumers.

For example, the food processing industry generates a phenomenal amount of waste each year, both in terms of packaging materials and wasted food. On top of this, different processing methods can alter food on a chemical level, which can lead to negative health impacts. To address these issues, Dr Vijaya Raghavan and his research team at McGill University have been investigating various aspects of the food processing industry, in order to develop and optimise methods.

Converting Seafood Waste into Useful Products

Seafood makes up a huge proportion of the food consumed worldwide. However, as seafood is particularly perishable, much work goes into

maximising its shelf life. During processing, the less desirable parts of fish, such as the head, scales, fins and bones, are typically discarded. Studies have shown that almost half of harvested seafood is wasted. Most of this seafood waste ends up in landfill, or is simply dumped back into the ocean – causing serious environmental problems.

Dr Raghavan and his colleagues have been working to address this problem

by developing methods that transform this waste into useful materials. In a recent study, they explored a technique known as hydrothermal carbonisation. This method, which converts biomass into useful carbon-rich materials, has been widely used to convert plant matter into a coal-like biofuel called hydrochar. However, it is far less commonly used for treating animal waste.

Typically, hydrothermal carbonisation is performed by raising the temperature of a material to around 200°C under high pressure and in the presence of water. Dr Raghavan and his team employed a modified version of this method, which uses microwave radiation for heating. Microwaves can heat an object by causing water molecules to rapidly rotate inside the object, which generates heat directly inside the material.

The team started the process by mashing fish waste in a blender and treating it with a cocktail of enzymes, to further break down the different components of the waste. Then, they placed the mixture in an enclosed container and heated it using microwave radiation. With heating, the pressure in the container increased, and under these conditions the waste became converted into hydrochar. The researchers collected and dried the hydrochar, and took samples for analysis.

They found that their hydrochar was of similar quality to that obtained from plant waste. This was very promising, as it meant that the team's seafood-derived hydrochar could be used as a sustainable, biofuel-based alternative to coal. Additionally, Dr Raghavan suggests that the hydrochar would make a good fertiliser for soil, extending its useful applications further. Liquid derived from the process is also valuable for several other applications.

The team's approach could revolutionise the fish processing industry, significantly cutting down on the amount of waste produced worldwide, while also providing new sustainable sources of energy, fertiliser and other products.

Reducing Risks for Allergy Sufferers

About 3% of the global adult population suffers from at least one type of food allergy, which represents a significant threat to their health. Peanut allergies are particularly serious, affecting roughly 1% of the US population. The prevalence of peanut allergies is largely because there are several different proteins in peanuts that can cause a dangerous immune response in affected people.

To add to this complexity, food processing can lead to structural changes in these proteins, making them more difficult to understand. In fact, certain structural changes to peanut proteins have been shown to reduce digestibility, and even increase the likelihood of triggering a severe allergic reaction compared to the unaltered protein. As peanuts are almost always processed before they reach the consumer, it is crucial to better understand the structural changes induced by different processing conditions.

Dr Raghavan and his colleagues have been investigating the nature of one particular peanut protein, called ARA-h-6. Through computational simulations, the team exposed this protein to different electric field strengths and various temperatures, to explore their effects on its structure. They found that while electric fields had a minor effect, increased temperatures did indeed have a large impact on the structure of the protein.

The team's work provides useful insights into how exactly this protein changes under various different processing conditions. Such computational simulations reveal far more structural detail compared to lab-based experiments, which only show the protein's structure before and after processing, without demonstrating what happens during the process. With further insights into the digestibility of different structures of ARA-h-6, and the forms that are likely to trigger an allergic

response, the team's insights could be used to develop new methods of processing peanuts to ensure healthier and safer foods.

Improving Digestibility of Soy-based Foods

In another study, Dr Raghavan and his team used computational simulations to explore structural changes in a protein found in soybeans. Specifically, they studied the effects of processing on the 'soybean trypsin inhibitor protein', which is known to block the action of enzymes that help us to digest other nutritional proteins. By better understanding how to change or destroy this protein's structure, its impact could be reduced, leading to soy-based foods that are more easily digested, and thus healthier.

In their study, Dr Raghavan's team found that the soybean trypsin inhibitor protein is unusually stable, and did not change much when exposed to different electric fields and elevated temperatures. Their research reveals the chemical and structural reasons behind this protein's stability, which may help scientists to develop ways of destroying it in a targeted way.

Hopefully, the insights gleaned in this study will inform the development of new methods for processing soybeans, to maximise the digestibility and nutritional value of soy-based foods. As soybeans are considered a more sustainable and ethical source of protein than meat, such methods would help to ensure the future sustainability of our food supply.

Drying Carrots with Microwaves

When it comes to preserving food, drying is a simple and effective processing method. It does not require any chemical additives and is often energy efficient. Therefore, much research goes into developing the best drying methods that do not sacrifice food quality.

One of the prominent methods used in this field is microwave drying. This works by heating the substance with microwaves, causing internal water to be driven to the surface where it evaporates. This process can also cause channels to open in the material as the water is removed, which in turn can lead to even faster drying times.

In order to achieve the most efficient drying using this method, the centre of the food needs to be much hotter than the surface, to optimise the movement of water. However, if the temperature difference is too large, heat-sensitive nutrients can be degraded and lost from the food. Therefore, Dr Raghavan has been investigating microwave drying, to better understand how it can be optimised.

His team uses carrots as a test food in their studies. The researchers began by cutting carrots into cubes with precise dimensions, which were submerged in hot water and then rapidly cooled. They then used a microwave drying unit that they had assembled using a microwave oven and a hot air generator. Using this setup, they performed a series of trials to monitor the internal and external temperatures of the cubes, as well as how much they decreased in size, and changes in their moisture content.

Through this, the team was able to determine the optimal conditions for drying carrot pieces, while maintaining the highest level of vitamin C. They were also able to identify the conditions that lead to the highest rehydration capacity, which is another important factor to consider.

Overall, the team's technique shows a lot of promise as a method for preserving carrots and other root vegetables, while also maintaining their nutritional value.

The Future of Food Processing

Dr Raghavan and his team have utilised their expertise in food chemistry and engineering to optimise various aspects of the food processing industry. Hopefully, their research and methods will soon be used by the food industry towards ensuring a more sustainable, safer and healthier future for all.

Meet the researcher

Dr Vijaya Raghavan
Department of Bioresource Engineering
McGill University
Quebec
Canada

Dr Vijaya Raghavan earned his BEng at Bangalore University, before obtaining his MSc in Agricultural Engineering from the University of Guelph, Ontario. He then pursued and completed his PhD at Colorado State University, before moving to a teaching position at McGill University, Quebec, where he holds his current position as a professor in the Department of Bioresource Engineering. Here, his research focuses on the methodology used in food processing, including storage and waste management, with a view to enhancing food security and sustainability. He has directed several projects funded by the Canadian Government and was recently made a Director of the Royal Society of Canada. In 2019, he was awarded with the Lifetime Achievement Award from the Society of Tropical Agriculture for significant contributions to the field.

CONTACT

E: vijaya.raghavan@mcgill.ca
W: https://www.mcgill.ca/bioeng/faculty-and-staff/vijaya-raghavan

KEY COLLABORATORS

Yvan Gariepy, McGill University
Dr Valérie Orsat, McGill University
Dr Arun Mujumdar, National University of Singapore
Dr Clément Vigneault, Agriculture and Agri-food Canada (AAFC)
Dr Michael Ngadi, McGill University
Dr Boris Tartakovsky, National Research Council Canada
Dr Animesh Dutta, University of Guelph
Dr Stéphane Godbout, Institut de receherche et de développement en agroenvironnement
Dr Nachimuthu Varadharaju, Tamid Nadu Agricultural University
Dr Satya Dev, Florida Agricultural and Machinery University
Dr Sai Vanga, Daiya Foods, Vancouver
Dr Zhenfeng Li, Jiangnan University
Dr Ashutosh Singh, University of Guelph
Dr Sakamon Devahastin, King Mongkut's University of Technology Thonburi
Dr Gabriella da Rosa, Universidade Federal do Pampa
Dr Marie-Josée Dumont, McGill University
Dr Mark Lefsrud, McGill University
Dr Darwin Lyew, McGill University
Dr Brenda Alvarez Chavez, GECA Environnement

FUNDING

Natural Sciences and Engineering Research Council of Canada (NSERC)
Fonds de recherche du Québec – Nature et technologies (FRQNT)
Ministère de l'Agriculture, des Pêcheries et de l'Alimentation (MAPAQ)
Canadian International Development Agency (CIDA)
International Development Research Centre (IDRC)
Canadian Foundation for Innovation (CFI)

FURTHER READING

W Xu, C Song, Z Li, F Song, S Hu, J Li, G Zhu, GSV Raghavan, Temperature gradient control during microwave combined with hot air drying, Biosystems Engineering, 2018, 169, 175.

S Kannan, Y Gariepy, GSV Raghavan, Optimization and characterization of hydrochar produced from microwave hydrothermal carbonization of fish waste, Waste Management, 2017, 65, 159.

BH Vagadia, SK Vanga, A Singh, V Raghavan, Effects of thermal and electric fields on soybean trypsin inhibitor protein: A molecular modelling study, Innovative Food Science & Emerging Technologies, 2016, 35, 9.

SK Vanga, A Singh, Vi Raghavan, Effect of thermal and electric field treatment on the conformation of Ara h 6 peanut protein allergen, Innovative Food Science & Emerging Technologies, 2015, 30, 79.

McGill UNIVERSITY

DAIRY BRAIN: A STEP TOWARDS SMARTER MANAGEMENT IN DAIRY FARMS

To manage their farms effectively, dairy farmers must base their decisions on real-time and continuous data streams, which collect information about feeding, milking, and an array of other factors. Dairy Brain is a toolkit introduced by **Dr Victor E. Cabrera** and his colleagues at the University of Wisconsin – Madison, which integrates the data streams collected by different software onto a single platform, and applies the latest algorithms to reveal novel insights. The technology could soon enable farmers and industry professionals to make far better use of the latest techniques in data analysis – and may even lead to new advances in efficiency and sustainability.

Modern Dairy Farming

Modern dairy farms produce and require vast amounts of data to operate. In order to optimise the efficiency of milk production, farmers must keep close track of various factors, including the nutritional requirements of their cows; the times at which they lactate; and the emergence of infections – all within herds containing thousands of animals.

In recent years, cutting-edge techniques have emerged that can handle these constant streams of data, containing diverse networks of sensors and robotic systems. These devices can be connected within the wider 'Internet of Things' (IoT), which allows the many interacting elements of dairy farms to freely exchange the data they need to operate efficiently. These innovations have led to a Big Data revolution in the dairy farming industry, and many farmers have come to fully embrace the technology.

Today, data collection techniques continue to evolve at an ever-growing pace. Their development has become a highly interdisciplinary field of research – involving farmers, data scientists, computer scientists, animal biologists, production management specialists, and industry professionals. However, this highly dynamic landscape is now presenting a new set of challenges.

Aiming for Integration

Currently, dairy farmers are finding it increasingly difficult to take full advantage of the opportunities presented by the latest data collection techniques. By collecting and analysing factors such as milking, feeding, reproduction, and cow behaviour, IoT systems can provide useful guidance for activities including nutritional management, selection of animals, and reproductive management.

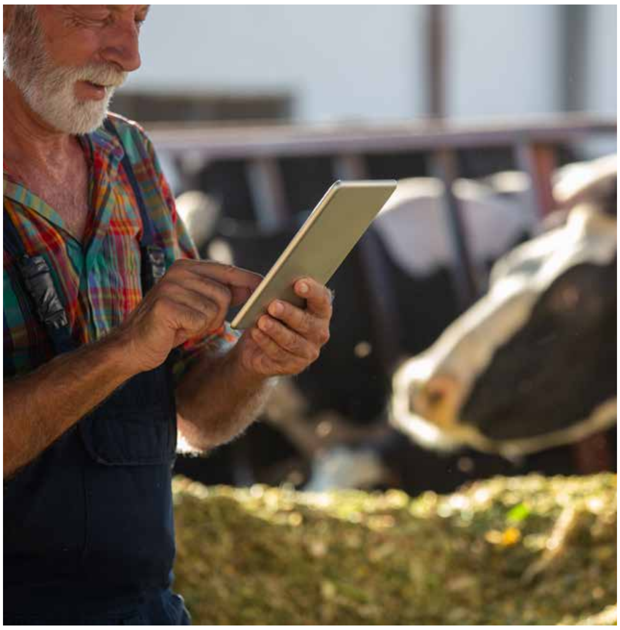
Yet these systems could go one step further. Since these factors can be closely linked to each other, it would be highly beneficial to farmers to link multiple data streams together. In turn, farmers would be able to gather even more useful insights into what is happening on their farms, allowing them to further improve their management decisions. Unfortunately, however, this isn't a simple task.

Within the IoT technologies often employed by modern dairy farms, data streams are typically visualised and interpreted separately, using different software tools. As a result, it can be incredibly difficult to link them together in real time when data streams are generated – despite the fact that they are closely interrelated. To overcome this challenge, researchers would need to develop a platform that can integrate all of the data streams collected on a farm. Through their research, Dr Victor E. Cabrera and his colleagues at the University of Wisconsin, Madison aim to reach this ambitious goal.

Developing a Smarter Platform

In 2019, Dr Cabrera's team founded 'UW-Dairy Brain' – a platform that integrates all of the most important software involved in dairy farm management. The project now comprises a Coordinated Innovation Network (CIN) of over 100 researchers, industry professionals, farmers, and other stakeholders from across the globe, alongside a collaboration of several large data processors – all working closely with Dr Cabrera's team at the University of Wisconsin. Now in its beta version, the technology incorporates a web-based interface, which allows users to access, integrate, and analyse multiple data streams.

Altogether, Dairy Brain operates by following five steps. Firstly, it transports the raw information from all relevant data streams into a centralised system. Then, it decodes and stores the information in a single database. Thirdly, Dairy Brain cleans the data to ensure that it can be used reliably; and then it expresses it in a uniform way, by identifying common features among the software used to collect each data stream. Finally, it integrates the data from these multiple different streams within a single location.



Each of these steps is crucial to make the data gathered from numerous different sources consistently available, and for developing new tools, capable of using this integrated data. So far, Dr Cabrera and his colleagues in the Dairy Brain, with the support of the CIN group, have examined the potential advantages of the platform in two particularly important applications.

Improving Nutritional Accuracy

To run their farms more efficiently, dairy farmers typically group their herds of lactating cows into pens. In doing this, their main concern is to keep management as simple as possible, by maintaining full pens, and producing the highest possible milk yield – all while minimising the amount of feed and nutrients the cows require in a group.

However, the nutritional requirements of different cows vary, depending on factors including their genetic makeup, stage of lactation, body weight, and whether or not they are pregnant. With inaccurate nutrition, some cows may become over- or under-fed – resulting in decreased productivity, and increased production costs.

To address these issues, more adequate approaches such as 'nutritional grouping' and 'providing more accurate' diets are now available. These techniques aim to better control costs and enhance efficiency on dairy farms, by collecting data on several different factors using specialised software, and using it to group cows into particular pens, depending on their nutritional requirements. In addition, they are able to formulate more accurate diets for each group of cows – all while respecting the unique practices of individual farms.

Despite these advantages, nutritional grouping has not been widely adopted by farmers. The problem is that an efficient platform has not yet been developed that can integrate the software required for each data stream – enabling farmers to deploy nutritional grouping within the unique constraints of their farms. Because of this, not all of the integrated data and algorithms required for the technique are available in a timely fashion, and many farmers believe that it adds unnecessary complexity to the management process.

By applying their Dairy Brain platform to the operation of actual farms in Wisconsin, Dr Cabrera's team has revealed feasible methods for implementing the strategy. Firstly, Dairy Brain integrates real-time data streams gathered separately by milking, feeding, management, and diet formulation software. Then, it groups cows according to their nutritional requirements, while respecting farm factors – such as prioritising grouping first according to the amount of milk they produce and their stage of lactation.

Based on this information, the platform provides lists of cows with similar nutritional requirements and calculates the diets they need to provide to comply with the group nutritional requirements at the least cost. This provides clear guidance for farmers as they split their herds into pens – allowing for better, simpler, and faster allocation of individual cows. Data from farms the team is working indicates that this strategy could reduce feeding costs by $31 per cow each year, which could amount to enormous savings and increased farm profitability.

Predicting Mastitis

Clinical mastitis is the most common disease experienced by dairy cows worldwide. It includes an inflammation in the udder tissue, which can be triggered by factors including physical trauma, overheating, and infection from microorganisms. In many cases, the condition will reduce milk quality and yield – but in the worst cases, it can prove fatal.

Although extensive research has now been done to prevent and treat mastitis, it still has a severe negative impact on dairy farm management. Through their latest research, Dr Cabrera's team has approached the issue using Dairy Brain's integrated data streams, again collected on actual Wisconsin farms.

In this case, Dairy Brain makes its predictions using machine learning – a form of artificial intelligence algorithms that can improve their performance through experience. Within the platform, data streams containing information about milking efficiency, genetics, and farm management are used to train the algorithms to make better predictions. Afterwards, real-time data streams can be used to reliably detect signs that are strongly associated with onset of mastitis – which may be virtually impossible for farmers to detect by themselves.

Altogether, the researchers ran two machine learning algorithms at the same time. The first of these allowed them to identify which particular cows are at higher risk of contracting mastitis during the first lactation. In the far shorter term, a second algorithm is able to predict when the risk of mastitis is imminent.

By including these two algorithms, the team hopes that Dairy Brain will provide a new dimension to health monitoring in herds – potentially detecting between 71 and 85% of all mastitis cases several milking sessions before the disease starts to take effect.

Success in Extensive Collaboration

Based on the success of these earlier studies, Dr Cabrera, together with his extensive team of collaborators within the Dairy Brain CIN, now hope to extend the capabilities of Dairy Brain even further. This will be made possible through extensive collaborations with a wide variety of researchers and organisations. As well as the US Council of Dairy Cattle Breeding, the team is working with data processors such as Valley Ag Software and Dairy Records Management Systems, to handle ever larger and more diverse datasets that will result in better decision making.

Together with Valley Ag Software and Bovisync, the researchers are also developing Dairy Brain's web-based interface to better retrieve, connect, integrate, and efficiently use the data gathered by actual dairy farms. As part of the diverse and extensive network of researchers and industry professionals, the Dairy Brain CIN is now actively exploring several exciting lines of research.

Already, the network has been instrumental in developing and implementing a survey initiative, which questioned farmers and industry professionals on issues relating to data governance. Elsewhere, they have published five magazine articles about dairy farm data ecosystems on Hoard's Dairyman and released a paper on decision support tools and another paper on data governance, and are now actively supporting other development aspects of the Dairy Brain platform.

Simulating Dairy Farms

Among these new projects is a collaboration between Dairy Brain and the 'Ruminant Farm System' (RuFaS) model national initiative, the next-generation, whole-farm model that simulates dairy farm production and environmental impact, which aims to provide the most rigorous tests yet for the Dairy Brain platform. So far, Dr Cabrera's team has used farms to assess the technology's performance. But in order to roll out the technology on larger scales, they will need to monitor thousands of farms over extensive periods of time – which would be far too expensive and time-consuming.

With the RuFaS interdisciplinary team, including researchers at Cornell, the University of Arkansas, University of California Davis, South Dakota State University and many USDA Agricultural Research Centres, Dr Cabrera and his colleagues

are now collaborating in the development of this dairy farm simulator – in which the widely varying parameters of dairy farms can be carefully adjusted. When completed, the RuFaS model will allow researchers to accurately analyse the management of entirely virtual herds. Crucially, RuFaS will be flexible enough to simulate and evaluate the many different operations and practices that take place on different types of dairy farm and, importantly, to use integrated data coming from the Dairy Brain.

The RuFaS is centred around key modules that simulate production, economics, transformations, and losses of nutrients, carbon, and water, across all of the main working elements of a dairy farm. RuFaS will ultimately provide ideal opportunities for the Dairy Brain to test their platform, as it integrates the data streams gathered in a diverse array of differing scenarios. As a result, it will soon be an important toolkit for their upcoming research.

Future-proofing the Dairy Industry

Today, the dairy industry is coming under increasing pressure to reduce its carbon emissions, while simultaneously meeting an ever-growing demand for dairy products worldwide. In the coming years, cutting-edge techniques for improving the efficiency and sustainability of dairy farms will become ever more important; and it will be crucial for farmers to take full advantage of the latest techniques in data analysis.

By integrating real-time data streams and the extensive information they contain onto a single platform, Dr Cabrera and his CIN colleagues ultimately hope that Dairy Brain will provide the first clear route towards this goal – preparing the dairy industry for the monumental challenges it could face in the coming decades.

Acknowledgement
This Dairy Brain project is being supported by the Food and Agriculture Cyberinformatics and Tools grant no. 2019-68017-29935/project accession no. 1019780 from the USDA National Institute of Food and Agriculture.

Meet the researcher

Dr Victor E. Cabrera
Department of Animal and Dairy Sciences
University of Wisconsin-Madison
Madison, WI
USA

Dr Victor Cabrera earned his PhD in Interdisciplinary Ecology at the University of Florida in 2004. He is now a Professor and Extension Specialist in Dairy Management at the University of Wisconsin-Madison, where his work includes the development of data-driven practical, user-friendly decision support tools for dairy farm management. Through these techniques, he aims to increase profits for dairy farms, while improving their long-term environmental sustainability. Dr Cabrera has received widespread recognition for his important work, including the Foundation Scholar Award in Dairy Production from the American Dairy Science Association, the DeLaval Dairy Extension Award and the Distinguished Achievement Award from the University of Florida School of Natural Resources and Environment.

CONTACT

E: vcabrera@wisc.edu
W: https://andysci.wisc.edu/directory/victor-cabrera/
W: https://dairybrain.wisc.edu/
W: https://DairyMGT.info
W: https://en.wikipedia.org/wiki/Victor_E._Cabrera

FUNDING

University of Wisconsin-Madison USDA Hatch and McIntire-Stennis
USDA National Institute of Food and Agriculture, Food and Agriculture Cyberinformatics
USDA National Institute of Food and Agriculture, Inter-Disciplinary Engagement in Animal Systems
USDA National Institute of Food and Agriculture, Critical Agricultural Research and Extension
University of Wisconsin-Madison Graduate School Research Competition
USDA National Institute of Food and Agriculture, Sustainable Agricultural Systems
University of Wisconsin-Madison, Office of the Vice Chancellor for Research and Graduate Education, UW 2020 Initiative
USDA National Institute of Food and Agriculture, Organic Agriculture Research and Extension Initiative
USDA National Institute of Food and Agriculture, Agriculture Economics and Rural Communities
USDA National Institute of Food and Agriculture, Integrated Solutions for Animal Agriculture
USDA Risk and Management Education and Outreach Partnership Program, Competitive Cooperative Partnership Agreements
USDA National Institute of Food and Agriculture, North Central Risk Management and Education Center

FURTHER READING

SR Wangen, F Zhang, L Fadul-Pacheco, TE da Silva, VE Cabrera, Improving farm decisions: the application of data engineering techniques to manage data streams from contemporary dairy operations, Livestock Science, 2021, 104602.

R Cue, M Doornink, R George, B Griffiths, MW Jorgensen, R Rogers, A Saha, K Taysom, VE Cabrera, SR Wangen, L Fadul-Pacheco, Data Governance in the Dairy Industry, Animals, 2021, 11, 2981. https://doi.org/10.3390/ani11102981

L Fadul-Pacheco, H Delgado, VE Cabrera, Exploring machine learning algorithms for early prediction of clinical mastitis, International Dairy Journal, 2021, 119, 105051.

VE Cabrera, JA Barrientos-Blanco, H Delgado, L Fadul-Pacheco, Symposium review: Real-time continuous decision making using big data on dairy farms, Journal of dairy science, 2020, 103, 3856.

JA Barrientos-Blanco, H White, RD Shaver, VE Cabrera, Improving nutritional accuracy and economics through a multiple ration-grouping strategy, Journal of dairy science, 2020, 103, 3774.

UW-Dairy Brain

IMPROVING LIVESTOCK THROUGH REPRODUCTIVE TECHNOLOGIES

Reproductive biotechnologies have contributed to many major advances in livestock production, and the proper application of these technologies can lead to livestock with superior genetic traits. This is vitally important given the high rates of malnourishment and poverty in developing countries, where communities could greatly benefit from an increase in meat and dairy products. Collaborating with scientists across the world, Dr Curtis R. Youngs of Iowa State University aims to increase the production of animal-derived foods in developing nations by applying reproductive biotechnologies to improve the efficiency and sustainability of livestock production.

Tackling Poverty and Malnutrition

Food insecurity impacts a third of the world's population and is hardest felt in developing nations. As the global population continues to soar, so too does the demand for protein, such as meat and dairy products, further threatening food security.

Livestock contribute directly to the livelihoods of families across the world by providing food, fibre such as wool, and income from selling these products. Livestock breeding on rural farms in developing countries is usually not highly organised, meaning that farmers are not achieving the full genetic and reproductive potential of their animals.

Enhancing the genetics of livestock through reproductive biotechnologies is a promising approach for improving the future livelihoods of farmers in developing countries. Such technologies include artificial insemination, in-vitro fertilisation, embryo transfer and pregnancy testing. Harnessing these methods would allow farmers to achieve herds consisting of healthier and more productive animals, and contribute to reducing malnutrition in their local communities. For instance, the use of artificial insemination in developed nations has boosted productivity in livestock, thereby allowing farmers to produce more food.

Dr Curtis Youngs of Iowa State University is working to help farmers in developing countries keep up with the increasing demand for animal-derived foods. By using a variety of reproductive biotechnologies to breed healthy, efficient and robust livestock, his team aims to reduce hunger and poverty in developing areas.

Their work will also reduce the environmental impact of animal production, improve animal welfare and increase the incomes of rural farmers. The additional income acquired from better quality livestock can help support improvements in education and infrastructure in these communities. Ultimately, Dr Youngs' work could help to inform new reproductive practices in developing countries worldwide.

Minimising Foetal Wastage and Disease in Camels

Livestock farming is crucial to the food security of rural populations in Algeria. Sheep, goats and cattle are abundant, but camels provide more than a third of the meat consumed in the southern region of the country. Furthermore, the demand for camel meat and milk is rising in Algeria and many other places worldwide.

Unfortunately, reproductive management practices are underutilised in the region, with many farmers not following standard mating practices for camels. Farmers typically rely on observation instead of testing to detect pregnancy, which often results in pregnant females being slaughtered, wasting future calves. The international team with whom Dr Youngs collaborates studied the prevalence of foetal wastage in Algeria and found that more than one in five female camels harvested for food were pregnant.

This represents a large economic loss to camel farmers, and ultimately results in reduced food production. Dr Youngs recommends that more effective management techniques, such as pregnancy testing in camels destined for harvest, could minimise foetal wastage, thereby enhancing food supply and improving the livelihoods of camel farmers in the region.

In addition to this problem, the research team studied risk factors for development of diseases impacting camel and human health. For example, their team was the first to document prevalence of a bacterium called *Chlamydophila abortus* in dromedary camels in eastern Algeria. Infection by this pathogen can cause a myriad of health issues in camels and can lead to abortion.

The prevalence of infection among 865 camels was 2.5%, while 15.8% of herds had at least one infected animal. Major risk factors for transmission include contact with sheep, goats and other camels through shared grazing and watering points, and introducing newly purchased animals to a herd. Similar studies were conducted for *Trypanosoma evansi*, BHV-1 and *Coxiella burnetii*, the latter being a zoonotic disease that adversely affects human health.

With the knowledge gained from these studies, control programs for these diseases can be designed and implemented in the region. The team's results illustrate the importance of health testing before purchasing a new animal and quarantining new animals before introducing them to the rest of the herd. Improved camel health will also enable greater meat and milk production.

Boosting Cattle's Reproductive Potential

Two of the most influential biotechnologies that have shaped livestock reproduction are artificial insemination and embryo transfer. Embryo transfer involves harvesting fertilised eggs from a genetically superior female and transferring them into a less valuable 'surrogate' female to continue development. This gives the breeder the opportunity to allow only genetically superior females to produce offspring, and those females can produce more offspring each year.

Very little is known about the reproductive physiology of the Boran cow, an endangered breed of cattle native to Ethiopia, which is well adapted to arid and semi-arid environments. Through collaboration with Ethiopian colleagues, Dr Youngs and his team have gained critical insight into the reproductive characteristics of these cows, which will aid efforts to maximise their reproductive performance and bring positive changes to cattle farmers of Ethiopia.

In one study, the research team investigated the 'superovulatory' response of purebred Ethiopian Boran cattle compared to Boran–Holstein crossbred cattle. Superovulation is the process of administering naturally-occurring hormones to induce the production of multiple eggs, which can then be used for reproductive technologies such as embryo transfer and in-vitro fertilisation. The aim of superovulation is to maximise the number of viable embryos that will result in successful pregnancies.

In cattle, follicle-stimulating hormone (FSH) is used to increase superovulatory response. However, Dr Youngs and his colleagues found that purebred Boran cows are more sensitive to this hormone than Boran–Holstein crossbred cows. Therefore, it is important to utilise a reduced dosage, as a higher dosage may disturb the process of ovulation and produce undesired results. Interestingly, the team found that purebred Boran cows yielded a higher number of good-quality embryos than their crossbred counterparts.

Reproductive Biotechnologies in Alpacas

Millions of alpacas live in high elevation areas of the Andean Mountains in Peru, Bolivia, Ecuador, and northern Chile, where the production of fibre from alpacas represents one of the most important rural economic activities. Alpacas have extraordinarily little environmental impact and are adapted to living under challenging conditions in which sheep and cattle cannot thrive. Alpaca rearing is an important source of employment and is a practical way to curb rural poverty in these regions. However, pregnancy rates of these animals are typically low, reducing their economic potential.

Working with colleagues in Peru, Dr Youngs has been testing different technologies to improve embryo transfer in South American alpacas and llamas. They are also investigating the best methods of processing alpaca sperm for use in assisted reproductive technologies, such as artificial insemination and sperm cryopreservation. Field-practical artificial insemination procedures have not been available for alpacas due to difficulties in obtaining useable samples, but the research team is making strides towards finding feasible solutions.

Dr Youngs and his team are also investigating whether freezing embryos might be a potential method to solve this problem. Such cryopreservation of embryos is commonly used to facilitate embryo transfer in sheep, goats and cattle, but very little research has been conducted with alpacas or llamas. Transporting frozen embryos is cheaper and poses a lower risk of disease transmission than moving live animals for the purpose of breeding.

The researchers conducted studies in the Peruvian Andes to compare the viability of alpaca embryos that had been cryopreserved by slow freezing or ultra-rapid cooling (also known as vitrification). They achieved the first pregnancies in alpacas after transfer of vitrified embryos, although no live births resulted from those pregnancies. However, in an ensuing study, Dr Youngs and his collaborators succeeded in producing the world's first alpaca born from a cryopreserved embryo. This successful outcome provides confidence for further use and development of this reproductive biotechnology in alpaca breeding programs.

After achieving a successful pregnancy and birth, the survival of the offspring is crucial for the economic viability of alpaca ranches and depends almost entirely on conditions during the first few days after birth. Therefore, Dr Youngs collaborated with a different Peruvian research team to assess the impact of various management systems on the survival and growth of alpaca offspring. Their work has shown that postnatal survival and daily body weight gain can be greatly enhanced by simply fitting newborn alpacas with an adjustable body vest.

Changing the Future of Livestock Reproduction

It is imperative to improve the efficiency of animal production in developing countries to reduce hunger and malnutrition, while mitigating the environmental impact of livestock production in those regions. Through their research into reproductive biotechnologies, Dr Youngs and his colleagues are helping to accomplish these goals.

In their future work, the researchers aim to continue developing genetic improvement programs. Enhancement of dairy cattle genetics in Kosovo, Uganda and Ethiopia is presently underway, with an eye towards improving livestock management and yields. The ultimate goals of Dr Youngs and his collaborators are to improve farmers' livelihoods, reduce hunger and malnutrition, improve animal welfare and reduce the environmental impact of livestock production in developing countries.

Meet the researcher

Dr Curtis R. Youngs
Department of Animal Science
Iowa State University
Ames, IA
USA

Dr Curtis R. Youngs earned his PhD in Animal Science from the University of Minnesota in 1985. After a year of postdoctoral training at Louisiana State University, he became an Assistant Professor at the University of Idaho. In 1989, he moved to Iowa State University, where he ultimately became a full professor in the Department of Animal Science. Here, he is also the Associate Director of Livestock and Animal Health Programs for the Center for Sustainable Rural Livelihoods & ME Ensminger Endowed Chair of International Animal Agriculture. Dr Youngs has trained many professionals and students in the technologies of artificial insemination and embryo transfer to increase the production of safe and nutritious meat and dairy products. Over the course of his career, he has earned many prestigious awards, including the Bouffault International Animal Agriculture Award. Dr Youngs also serves on the editorial boards for two scientific journals and is a member of many professional societies.

CONTACT

E: cryoungs@iastate.edu
W: https://www.ans.iastate.edu/people/curtis-youngs

FURTHER READING

S Valenzuela, RM Benites, JE Moscoso-Munoz, CR Youngs, OE Gomez-Quispe, Impact of cria protection strategy on post-natal survival and growth of alpacas (*Vicugna pacos*), Veterinary and Animal Science, 2021, 11, 100162. https://doi.org/10.1016/j.vas.2020.100162

Benaissa, MH, N Mimoune, B Faye, Y Bentria, FZ Mimouni, CR Youngs, and R Kaidi, First serological evidence of BHV-1 virus in Algerian dromedary camels: Seroprevalence and associated risk factors, Comparative Immunology, Microbiology, and Infectious Diseases, 2021, 76, 101638. https://doi.org/10.1016/j.cimid.2021.101638

JC Lutz, SL Johnson, KJ Duprey, PJ Taylor, HW Vivanco-Mackie, MD Ponce-Salazar, M Miguel-Gonzales, CR Youngs, Birth of a live cria after transfer of a vitrified-warmed alpaca (*Vicugna pacos*) preimplantation embryo, Frontiers in Veterinary Science, 2020, 7, 581877. https://doi.org/10.3389/fvets.2020.581877

MH Benaissa, N Mimoune, CR Youngs, R Kaidi, B Faye, First report of Chlamydophila abortus infection in the dromedary camel (*Camelus dromedarius*) population in eastern Algeria, Comparative Immunology, Microbiology and Infectious Diseases, 2020, 73, 101557. https://doi.org/10.1016/j.cimid.2020.101557

Benaissa MH, Y Bentria, N Mimoune, T Kernif, A Boukhelkhal, CR Youngs, R Kaidi, B Faye, and Y Halis, Seroprevalence and risk factors for Trypanosoma evansi, the causative agent of surra, in the dromedary camel (*Camelus dromedarius*) population in southeastern Algeria, Onderstepoort Journal of Veterinary Research, 2020, 87, a1891. https://doi.org/10.4102/ojvr.v87i1.1891

OE Gómez-Quispe, GA Gutiérrez-Reynoso, A Gallegos-Cardenas, FG Fumuso, M Asparrin, M Asparrin-Del Carpio, WC Jara, D Ponce, M Miguel, CR Youngs, HW Vivanco, Motility and recovery of alpaca (*Vicugna pacos*) spermatozoa after centrifugation in a density gradient solution, Iranian Journal of Veterinary Research, 2019, 20, 96–104. https://doi.org/10.22099/ijvr.2019.5257

HW Vivanco-Mackie, MD Ponce-Salazar, M Miguel-Gonzales, CR Youngs, C Jara, M Asparrin, Comparative study between slow freezing and vitrification on the survival rate of cryopreserved alpaca embryos post-transfer Reproduction, Fertility and Development, 2018, 31, 182.

T Degefa, A Lemma, E Demissie, S Ali, A Funga, CR Youngs, Superovulation response and in vivo embryo production potential of Boran cows in Ethiopia, Ethiopian Journal of Agricultural Sciences, 2018, 28(1), 71–80. https://www.ajol.info/index.php/ejas/article/view/182191

Benaissa MH, S Ansel, A Mohamed-Cherif, K Benfodil, D Khelef, CR Youngs, R Kaidi, and K Ait-Oudhia, Seroprevalence and risk factors for *Coxiella burnetii*, the causative agent of Q fever in the dromedary camel (*Camelus dromedarius*) population in Algeria, Onderstepoort Journal of Veterinary Research, 2017, 84, a1461. https://doi.org/10.4102/ojvr.v84i1.1461

MH Benaissa, B Faye, CR Youngs, R Kaidi, Slaughterhouse survey of culled female camels (*Camelus dromedarius*) in southeast Algeria: Fetal wastage and pregnancy characteristics, Emirates Journal of Food and Agriculture, 2016, 28, 805–812. https://doi.org/10.9755/ejfa.2016-06-735

T Degefa, A Lemma, J Jemal, G Mamo, A Tegegne, CR Youngs, Ovarian follicular dynamics in purebred and crossbred Boran cows in Ethiopia, African Journal of Biotechnology, 2016, 15, 1763–1770. https://doi.org/10.5897/AJB2016.15267

HW Vivanco-Mackie, MDP Salazar, M Miguel-Gonzales, CR Youngs, M Asparrin, Embryo survival to calving according to type of embryo and embryo transfer methods in alpacas, Reproduction, Fertility and Development, 2014, 27, 173–173.

A BRIGHT FUTURE FOR TRANSGENIC LIVESTOCK

Advancements in genetic technologies have made precise gene editing a reality. Used extensively to develop crops that exhibit higher yields and resistance to pests and diseases, genetic modification could also transform livestock production. Building on decades of animal cloning research, **Dr Mark Westhusin** from the Reproductive Sciences Laboratory at Texas A&M University is using genetic and reproductive technologies to improve livestock for food, medicine, and medical research.

It Started with Cloning

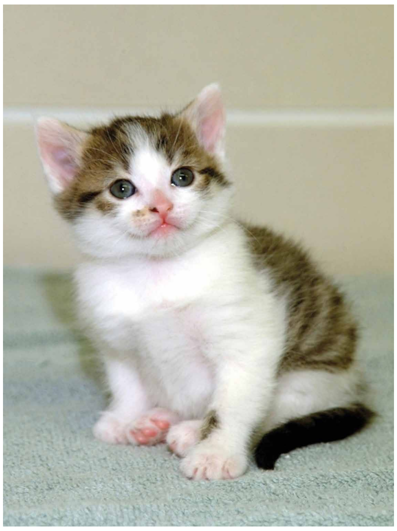
Dolly the sheep became an overnight sensation when researchers from the Roslin Institute introduced her to the world in February 1997. The possibilities of cloning gripped imaginations the world over – but the concept was far from new at the time of Dolly's birth.

Naturally occurring 'clones' – or individuals that are genetically identical – exist in mammals in the form of identical twins. As early as 1979, scientists had artificially replicated this process in mice, by extracting the DNA-containing nucleus from an embryo cell, inserting it into a mouse egg, and then implanting the egg into the womb of an adult mouse. By the time Dolly came along, genetically identical cows and sheep had been produced by transferring the nucleus from an early embryo cell into an egg cell.

It was not until Dolly, however, that a clone had been created from a fully-formed 'somatic' – or non-reproductive – cell. During development, somatic cells go through a process of differentiation to become all the tissues required to form a whole animal, for example, skin or muscle. But as cells mature, they lose the ability to differentiate. Many scientists had presumed the process of differentiation in mammalian cells was irreversible.

'Somatic cell nuclear transfer' – the process used to create a clone of an adult animal – made creating genetic replicas of prized livestock or beloved pets a reality. The news captured the attention of wealthy businessman, John G. Sperling, who enlisted the help of experienced scientists at Texas A&M University's Reproductive Sciences Laboratory (RSL) to clone his beloved collie-husky mix, Missy. Drawing on decades of previous research on reproductive technologies by RSL's director Dr Mark Westhusin, efforts to create a clone of Missy began – and the 'Missyplicity Project' was born.

As it turned out, cloning dogs is extraordinarily difficult, in part, due to their unique reproductive cycle and the difficulty in obtaining viable eggs that can be used to produce cloned embryos. Dogs are only fertile once every 6 to 12 months, and do not respond to hormone treatment, making it extremely difficult to produce large numbers of embryos and transfer them into recipient females. 'But, with the media announcement regarding our efforts to clone Missy, we had an enormous number of inquiries from people interested in also cloning cats, which were a lot easier,' says Dr Westhusin. 'So, we did that first.' On the 22nd of December, 2001, the world's first cloned pet, a grey and white tabby cat, affectionately called 'CC', was born via caesarean section.



'CC', the world's first cloned pet

Subsequently, researchers at RSL along with a number of other colleagues at Texas A&M University's College of Veterinary Medicine cloned pigs, cattle, goats, horses, and the world's first white-tailed deer. RSL holds the honour of having cloned more species than

any other institution in the world. No small feat, considering the effort involved. 'In many instances, methods that work in one animal species cannot be easily adapted to another, resulting in the need for extensive research along with "trial and error" approaches to try and develop methods that result in a successful outcome,' explains Dr Westhusin.

In addition to being helpful for devoted pet-owners, cloning provides a method of preserving or rescuing valuable genomes. Take for instance, the College of Veterinary Medicine at Texas A&M University's black angus bull, Bull 86. After testing hundreds of cattle, Bull 86 was discovered to have a natural – or genetic – resistance to brucellosis, tuberculosis, and other serious diseases that can be transferred between herds and even to humans.

Bull 86 provided a unique research opportunity that would have been lost when he died in 1998, had it not been for a rescue cloning operation by Dr Westhusin and his colleague Dr Taeyoung Shin. Bull 86's clone, called Bull 86^2 – or 86 squared – for his exponential genetic potential, has allowed research of his valuable genetic makeup to continue. '86 squared was cloned using cells that had been frozen for genetic analysis, in 1988, nearly 10 years prior to the birth of Dolly and at a time when the idea of cloning from somatic cells was thought to be impossible,' says Dr Westhusin.

A New Era: Genetic Modification

Cloning pets and livestock was not, however, the end goal for Dr Westhusin. By combining the techniques he and his associates developed during his cloning research with gene editing technology, Dr Westhusin aims to produce genetically modified – or 'transgenic' – livestock that could help solve global issues, such as future food security for the rapidly expanding human population. He identifies three key areas in which transgenic livestock could be a game changer: agriculture, medical research, and medicines.

The molecular tools used to edit genes have advanced rapidly since the technology's infancy. Now, scientists can engineer helper enzymes to perform an array of functions on targeted areas of the host DNA. For example, scientists can identify and use specific enzymes to cleave open the DNA and insert a new gene in a precise location with incredible accuracy. This technology can be used to edit the DNA of somatic cells growing in a laboratory culture. Somatic cell nuclear transfer – the same technique used to create animal clones – can then be used to create viable transgenic animals.

Animal Agriculture

The vast potential of genetic modification is already being realised for crops, with the number approved for commercial cultivation increasing each year. Scientists have developed crop plants that are resistant to drought, pests and diseases, have higher yields, are tastier, and even have enhanced nutritional benefits. In fact, the vast majority of cotton, corn, soybeans and wheat we consume today has already been genetically modified.

Transgenic livestock have been lagging behind, partly due to prohibitive regulations. In 2015, Aquabounty's salmon became the first transgenic animal to gain approval for food production in the USA. Early in 2021, a line of pigs was approved. Albeit a slow process, the negative perceptions surrounding genetic modification are changing, and changes to transgenic livestock regulations could soon follow.

Genetic disease resistance could help improve animal welfare and prevent diseases spreading to other animals and humans. Genetic engineering offers immense opportunities to develop parasite and disease resistant transgenic livestock. With the aim of eventually transferring the technique to cattle, Dr Westhusin has been developing methods to inactivate the gene responsible for prion protein production – the errant protein responsible for mad-cow disease and Creutzfeldt-Jakob disease. A number of years ago, he successfully produced a transgenic goat foetus that exhibited a 90% reduction in

Goats that produce a malaria vaccine in their milk

the prion protein gene activity when compared with a non-transgenic goat foetus of the same age. 'Subsequent work in other laboratories has now resulted in cattle with the prion gene inactivated,' says Dr Westhusin.

He has also focused efforts on producing transgenic livestock with increased muscle growth and development by inactivating a growth-limiting gene, myostatin. Increasing the production of meat or milk in livestock improves feed efficiency, and thus sustainability and agricultural production costs. Additionally, the UN Food and Agriculture Organization (FAO) estimates that food production will need to increase by 70% by 2050 to meet demands – transgenic livestock could help us achieve this goal and ensure future food security.

Biomedical Research

Genetic technologies also offer unprecedented opportunities for biomedical research. Appropriate and reliable animal models are needed to replace rodents as the predominant species used, as they are often poor comparisons for human physiology. Sheep and pigs offer better alternatives. However, non-rodent animal models are prohibitively expensive. Efficient genetic modification could reduce the costs involved and make large animal models a viable alternative.

Accurately replicating human diseases in animal models is an important component of understanding disease progression and the development of treatments. Dr Westhusin and his collaborators successfully produced the first large animal model of a rare human bone disease called hypophosphatasia. The researchers disrupted the function of a gene involved in mineral metabolism – the same gene that causes the bone disease in humans when not functioning correctly.

The transgenic sheep developed similar patterns of bone and tooth development as observed in humans with hypophosphatasia, including decreased sacral vertebrae size, short teeth roots, and small jaw bones. Because the transgenic sheep accurately copy the disease presentation in humans, they provide a novel large animal model that will allow long-term research of the disease progression, and could contribute to the study of other rare bone diseases.

Medicines and Therapeutics

One of the most promising uses for transgenic livestock is as living bioreactors to produce vaccines and other medicines in their milk. This offers a significant economic saving in comparison with maintaining cell cultures for the same purpose, because animals are extremely efficient at producing therapeutic substances in their milk. For example, an advanced facility for housing and maintaining a small herd of transgenic goats may cost around $20 million USD, replacing a comparative cell culture facility that could cost in the region of $750 million to $1 billion USD. 'It has been estimated that a single goat, over a single lactation cycle in one year, could produce the equivalent of 8 million doses of vaccine,' says Dr Westhusin. 'Imagine if we had a herd of goats producing vaccines for COVID-19!'

In 2010, Dr Westhusin and colleagues at RSL teamed up with LFB Inc. to develop transgenic goats that produce malaria vaccine in their milk. Around 400,000 people die each year from malaria. The disease disproportionately affects developing countries, where funding is often not available to pay for the vaccines they so desperately need. Transgenic livestock which produce the vaccine in their milk could solve this problem. 'A small herd of goats would be capable of producing all the malaria vaccine needed in the entire world!' says Dr Westhusin.

Using frozen semen and assisted reproductive techniques, the researchers successfully produced three transgenic goats, two males and one female. Analysis of the milk produced by the female confirmed malaria vaccine production. So far, the scientists have tested the vaccine in mice, demonstrating its effectiveness in preventing malaria. The next stages include additional testing involving non-human primates to demonstrate the safety and efficacy of the vaccine, required for regulatory approval.

A Bright Future

By applying techniques to inactivate individual genes, Dr Westhusin is currently investigating how each contributes to normal development of cattle embryos, including during the sensitive pre-implantation stage. He is also exploring new genetic modification approaches that could improve efficiency and help prevent developmental abnormalities in transgenic and cloned livestock.

With over 125 years of combined experience in mammalian reproduction, Dr Westhusin and his colleagues are trailblazing the research in transgenic livestock development. RSL scientists have used their approach to produce over a hundred transgenic animals, including cattle, goats, sheep, and pigs. Soon their techniques could be expanded to include even more species, and could offer novel solutions for many more global issues.

Meet the researcher

Dr Mark E. Westhusin
Department of Veterinary Physiology and Pharmacology
Texas A&M University
College Station, TX
USA

Dr Mark E. Westhusin holds the position of Professor within the Department of Veterinary Physiology and Pharmacology at Texas A&M University, where he is also co-director of the Reproductive Sciences Laboratory. Raised on a farm in Kansas, Dr Westhusin obtained his BS in Animal Science at Kansas State University, and then moved to Texas, where he completed both his master's and PhD at Texas A&M University. His research is focused on biotechnology, cloning and genetic engineering of animals. He has received numerous honours, including the NIH Director's Award, American Society of Animal Sciences Scholarship Award, Pfizer Research Award, the Richard H. Davis Teaching Award and a TAMU Alumni Distinguished Achievement Award in Research. Dr Westhusin has had over 75 scientific papers published in prestigious journals, including Nature and Science. He has also given over 60 invited talks internationally and contributed to several books. In addition to his research activities, Dr Westhusin teaches across a range of undergraduate and graduate courses and has mentored over 50 graduate students.

CONTACT

E: m-westhusin@tamu.edu
W: https://physiology.tamu.edu/faculty/mark-e-westhusin/

KEY COLLABORATORS

Charles Long, College of Veterinary Medicine and Biomedical Sciences, Texas A&M University
Duane Kraemer, College of Veterinary Medicine and Biomedical Sciences, Texas A&M University
Michael Golding, College of Veterinary Medicine and Biomedical Sciences, Texas A&M University
Larry Suva, College of Veterinary Medicine and Biomedical Sciences, Texas A&M University
Dana Gaddy, College of Veterinary Medicine and Biomedical Sciences, Texas A&M University
William Gavin, Chief Operating Officer, LFB-USA.

FUNDING

National Institutes of Health
United States Department of Agriculture
Texas Agrilife Research
Bioarts Inc.

FURTHER READING

DK Williams, C Pinzon, S Huggins, JH Pryor, A Falck, F Herman, J Oldeschulte, MB Chavez, BL Foster, SH White, ME Westhusin, LJ Suva, CR Long, D Gady, Genetic engineering a large animal model of human hypophosphatasia in sheep, Scientific Reports, 2018, 8, 16945. DOI: 10.1038/s41598-018-35079-y

K Tessanne, MC Golding, CR Long, MD Peoples, G Hannon, ME Westhusin, Production of transgenic calves expressing an shRNA targeting myostatin, Molecular reproduction and development, 2012, 79, 176. DOI: 10.1002/mrd.22007

ME Westhusin, T Shin, JW Templeton, RC Burghardt, LG Adams, Rescuing valuable genomes by animal cloning: a case for natural disease resistance in cattle, Journal of Animal Science, 2007, 85, 138. DOI: 10.2527/jas.2006-258

MC Golding, CR Long, MA Carmell, GJ Hannon, ME Westhusin, Suppression of prion protein in livestock by RNA interference, Proceedings of the National Academy of Sciences, 2006, 103, 5285. DOI: 10.1073/pnas.0600813103

T Shin, D Kraemer, J Pryor, L Liu, J Rugila, L Howe, S Buck, K Murphy, L Lyons, ME Westhusin, A cat cloned by nuclear transplantation, Nature, 2002, 415, 859. DOI: 10.1038/nature723

TEXAS A&M UNIVERSITY

PROTECTING PALAU'S FOOD SECURITY AND MARINE ECOLOGY USING SATELLITE TECHNOLOGY

Palau, a remote group of islands in the Pacific Ocean, relies heavily on wild fish to feed its citizens and support its economy. With a growing population and thriving tourism industry, the country cannot afford a crash in catch size. However, climate change is altering the ecosystems of Palau's fishing waters, threatening harvests of important fish species. To improve the country's food security and accelerate the achievement of the UN's Sustainable Development Goals, the Palauan Government has teamed up with the Nature Conservancy to build a sustainable aquaculture community on the islands, with support from NASA. Using NASA satellite observations, the collaboration helps aquaculture farmers to find optimum locations to farm fish and shellfish, allowing them to produce an abundance of seafood while protecting the surrounding marine environment.

Palau's Dwindling Seafood Supply

Palau is a remote cluster of 340 small islands in the Pacific Ocean, just over 1000 kilometres east of the Philippines, with a population of fewer than 23,000 citizens and a land area roughly half the size of New York City. The average Palau resident consumes 67.7 kilos of seafood each year; that's over three times the global average. This makes Palau's fishing industry vital for the country's food security and economy.

Similar to many other countries around the world, Palau relies on its seafood industry as a major source of protein. With a growing population and booming tourism industry, there is an increased strain on resources. This means that the country could struggle to provide enough seafood for the population while reducing negative impacts on the environment. This is especially challenging given current climate change, which is altering marine habitats and reducing wild fish populations.

Palau's marine ecosystem is particularly sensitive to climate change. Many of the islands lie close to the 'Coral Triangle', which boasts the highest biodiversity of any shallow-reef ecosystem on Earth. This means that small changes in temperature can dramatically alter the abundance and diversity of fish and other marine species that live around the islands. Palau's annual catch has already decreased in recent years, and this is expected to drop by a further 25% by 2050 due to climate change.

Aside from fish and shellfish, Palau imports most of its other food, due to limited arable land on the islands. Therefore, the projected decrease in fresh seafood is a serious cause for

concern. With a reduced supply of nutritious seafood, many people may turn to eating more processed food, such as canned meat. Processed food is already popular in Palau, and is a major factor behind the country's rising levels of obesity and diet-related conditions. It is therefore clear that fresh seafood needs to remain abundant to ensure the future health of Palau's citizens.

The Role of Aquaculture

The instability of wild fish stocks around Palau, and the increasing demand for seafood from residents and tourists, call for new approaches to ensuring the country's future food security. This is where marine aquaculture comes in. Marine aquaculture involves the farming of aquatic organisms such as fish, shellfish and seaweed, typically within pens or cages in coastal waters. This method has the potential to be a sustainable alternative to catching wild seafood.

'When aquaculture is well located and properly managed, it provides a sustainable alternative to wild fisheries,' explains Jonathan MacKay, a marine spatial scientist at the Nature Conservancy (TNC). 'However, when aquaculture is improperly sited and managed, it can result in a suite of negative impacts on the environment and communities, including habitat degradation and poor water quality.'

Therefore, aquaculture planning and management is vitally important to make sure there is enough seafood to feed the population, without causing long-term environmental degradation. However, sustainable practices can be difficult to implement when seafood is in such high demand, and is also responsible for propping up a large portion of the country's economy.

Some attempts have been made to combat this issue, such as a farm loan program designed to support aquaculture farmers in the country. However, when applying to the program, the applicant must provide a proposal that details how and where the farming can be carried out in a sustainable fashion. This is incredibly difficult to assess without adequate technology and other resources, meaning that many farmers are ineligible for the loan.

Indeed, aquaculture farmers in Palau have appealed for help with identifying appropriate locations for their aquaculture operations, as it is prohibitively expensive and time-consuming to conduct environmental assessments on potential sites themselves.

Therefore, it is apparent that aquaculture support plans should first focus on equipping farmers with the resources, technology and knowledge they need to produce seafood in a way that is not detrimental to the environment.

A New Collaboration

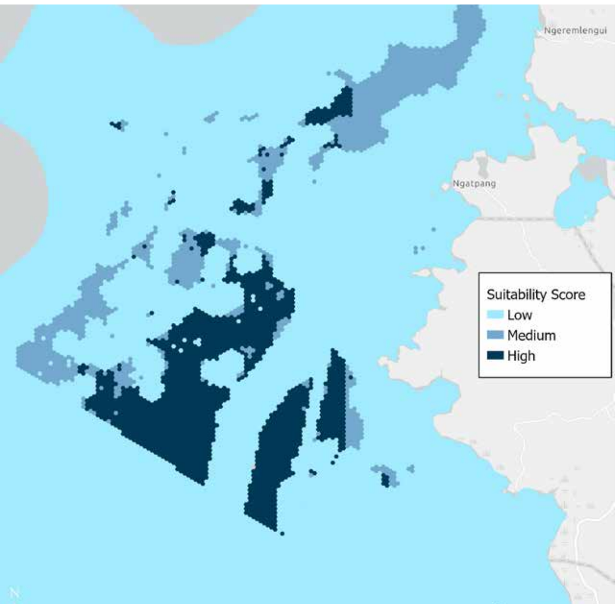
A new management strategy was unveiled in 2016 by Palau's President Tommy Remengesau, with the aim of promoting sustainable aquaculture to ensure the country's future food security. 'Palau cannot continue to rely entirely on the wild when it comes to subsistence and commercial food production,' he declared. Palau's incoming President, Surangel Whipps Jr., has similarly identified aquaculture as a priority within his new administration.

Sustainable aquaculture lies within the core of the country's economic development plan. However, being a small and remote cluster of islands, Palau does not currently host the technology needed for sustainable aquaculture development. Therefore, the Palauan Government has teamed up with NASA, TNC and other organisations, to build a thriving and sustainable aquaculture industry. In particular, NASA satellite observations will be utilised to help farmers determine locations for their aquaculture operations that will have the least environmental impact.

'Our research brings together the power of NASA data and technology to help inform marine spatial planning for sustainable marine aquaculture,' says Jonathan MacKay, a key member of the collaboration. 'The overall goal of the project is to improve food security in Palau while ensuring Palau's unique and pristine marine environment is protected.' MacKay and his colleagues' project began in 2018 and plans to run until the end of 2022.

'The project will work to acquire relevant data, perform necessary analyses, and develop web applications to inform climate-ready aquaculture spatial planning and management,' says Robert Jones of TNC, who leads the collaboration. He explains that their work aims to 'create the enabling conditions for sustainable aquaculture sector development in Palau that will yield a climate-ready source of healthy food for its citizens.'

In doing so, the project will accelerate the achievement of three of the UN's Sustainable Development Goals: life below water, climate action, and good health and well-being.



Identifying Ideal Sites

According to MacKay, one important factor to consider when finding an ideal aquaculture site is the water depth. If the water is too shallow, waste produced from aquaculture operations can accumulate on the seabed, damaging seafloor ecosystems.

In a 2020 study, the team reviewed siting standards around the world and incorporated input from stakeholders on environmental and economic feasibility to determine the ideal ocean depths for aquaculture around Palau. In a separate study, researchers created a dataset by combining images from the NASA satellite Landsat 8 and depth values collected on the water to accurately map the seafloor around Palau.

In addition to depth data, several project members are also using climate forecasting to indicate areas that are least sensitive to climate change. Specifically, they are identifying locations where ocean temperatures are changing most slowly, as these regions are considered to be the most desirable to for setting up aquaculture operations. This is because large increases in temperature could impact the health of farmed fish and shellfish, for example by facilitating the spread of disease and pests that thrive in warmer water.

Other factors that must be taken into account include the presence of critical habitats, such as coral reefs and seagrass beds, which are being identified using different datasets from the NOAA and Allen Coral Atlas. The collaboration also considers the distributions of dugongs and other protected species, along with coastal areas that are commonly used for recreation and those that frequently experience dangerous algal blooms. When considering potential aquaculture sites, such regions must be avoided.

MacKay and his collaborators incorporate all of these factors and many more into their suitability analysis to identify optimum locations. 'By incorporating sustainability factors into a spatial analysis, the results can ensure that the site avoids use conflicts, sensitive habitats, and are economically viable,' he says.

Using the results of this comprehensive analysis, other collaborators on the project aim to create a custom online data-viewing platform, which will provide users with up-to-date data to indicate the best locations for sustainable aquaculture.

Building Capacity

As part of the project, several collaborators based at TNC are also providing training modules to train Palauan government representatives on spatial planning methods and suitability mapping. This training program aims to equip the people of Palau with the skills and knowledge they need to expand their aquaculture industry in a sustainable and environmentally friendly way. The collaboration has also prepared a guidance manual to help with planning, management, and implementing sustainable policies.

The collaboration is hopeful that this project will be the first to have a long-lasting positive impact on Palau's seafood industry, future food security and public health. In the coming years, MacKay and Jones hope that their work will lead to the development of a thriving and sustainable aquaculture industry that helps meet different aspects of the UN's Sustainable Development Goals. As MacKay concludes: 'Already, we've brought together farmers, government partners, local universities together to work towards achieving a mutual goal of developing Palau's aquaculture industry that benefits food security and preserves Palau's pristine marine environment.'

Meet the researchers

Jonathan MacKay
Marine Spatial Scientist – Aquaculture Contractor
CSS Inc, in support of The Nature Conservancy
San Francisco, CA, USA

Jonathan MacKay is a Marine Scientist with over a decade in the profession, seven of which have been dedicated to advancing sustainable aquaculture. MacKay earned his Bachelor's degree in Marine Science from The University of the South Pacific, Fiji, before progressing to a Master's in Environmental Science from California State University, Los Angeles. Upon graduating, he worked as a California Sea Grant Fellow on the Aquaculture Program at the California Department for Fish and Wildlife. Since February 2020, MacKay has been working as an Aquaculture Marine Spatial Scientist with The Nature Conservancy, and the National Ocean Atmospheric Administration (NOAA). He is also a UCLA certified AAUS Scientific Diver, and PADI certified Divemaster.

CONTACT

E: jonathan.mackay@tnc.org

Yvonne Ueda
Micronesia Fisheries Project Manager
The Nature Conservancy
Koror, Palau

Yvonne Ueda was born and raised in the island of Palau. Ms Ueda is currently the Micronesia Fisheries Project Manager for The Nature Conservancy Micronesia Program and is based in Palau. Her role provides day-to-day management, leadership and implementation of the Conservancy's coastal fisheries projects in the Republic of Palau. Prior to The Nature Conservancy, Ms Ueda served 12 years in the Government, in the Ministry of State as the Foreign Service Officer coordinating activities with various countries, regional and international organisations to support Palau, negotiating treaties, aids and other technical support ensuring Palau's interests and policies are represented.

CONTACT

E: yvonne.ueda@tnc.org

Mike Aulerio
Geographic Information System Specialist & Conservation Information Manager II
The Nature Conservancy
Koror, Palau

As Geographic Information System Specialist and Conservation Information Manager II, Mike Aulerio is responsible for GIS technical services in support of conservation activities, both marine and terrestrial, of the Conservancy Micronesia Program and its government and non-government partners in the five Micronesian jurisdictions. In addition, he will also provide similar support to other Conservancy's programs within the Pacific Island Countries Operation Unit. Before joining the Conservancy in 2007, Mike worked for the Office of PALARIS, Palau, Ministry of Resource and Development for seven years as Assistant GIS Analyst. He also regularly teaches GIS at Palau Community College under the Operation Management Improvement Project.

CONTACT

E: maulerio@tnc.org

Robert Jones
Global Aquaculture Lead
The Nature Conservancy
Arlington, VA
USA

Robert Jones is an expert in the field of aquaculture, with over a decade of experience in this area. Jones directs the Global Aquaculture Program at The Nature Conservancy, where he leads projects in seven countries around the world. In 2012, he was awarded his Master's degree in Marine Affairs and Policy, with a focus on aquaculture and fisheries, from the University of Miami. Since then, he has worked in a variety of important institutes, including the US National Marine Fisheries Service Office of Aquaculture, and the US Department of State Office of Marine Conservation. In 2019, he was a Robert B. Wilson Harvard Business School Fellow for Environmental Leadership.

CONTACT

E: robert.jones@tnc.org

KEY COLLABORATORS

The Nature Conservancy
Palau Environmental Quality Protection Board
Palau Ministry of Agriculture, Fisheries, and Environment
Palau Community College

FUNDING

National Aeronautics and Space Administration – award number: 80NSSC19K0188

The Nature Conservancy

EXPLORING HOW FISH ADAPT TO CLIMATE CHANGE: SUSTAINABLE AQUACULTURE AND SPECIES CONSERVATION

With the global population increasing at a considerable rate, it is becoming vitally important to improve seafood production to meet the growing demand for healthy protein. As our current fishing practices are damaging to marine ecosystems, fish farming is seen as a sustainable alternative to producing seafood, but only if it is resilient to the effects of climate change. By researching how environmental change affects fish biology, **Dr Kurt Gamperl** of Memorial University of Newfoundland and Labrador and his colleagues aim to make fish farming more sustainable, while ensuring global food security and allowing wild fish populations to recover.

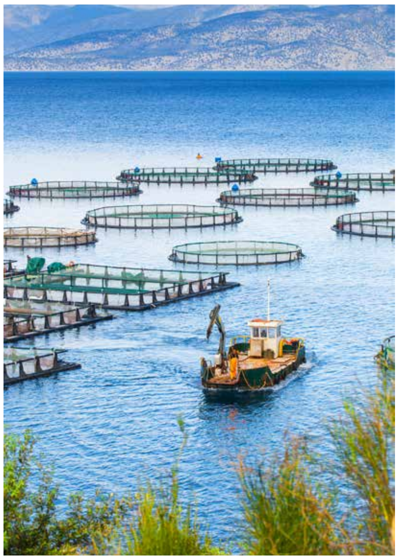
The Future of Seafood Production

Fish are a crucial component of a nutritious diet in many parts of the world, providing a healthy protein source and playing an important role in eliminating hunger and malnutrition. With the global population expected to reach nearly 10 billion by 2050, the Food and Agriculture Organisation (FAO) of the United Nations estimates that food production will need to increase by 70%. Fish will continue to play an important role as this population growth continues.

However, overfishing has led to worrying declines in wild fish populations across the globe. Climate change is also having a damaging impact, as rising ocean temperatures and acidity can devastate marine ecosystems. Therefore, breeding, rearing and harvesting fish in captivity – known as aquaculture – represents a sustainable alternative to fishing, which greatly reduces the pressure on wild fish stocks.

Indeed, aquaculture is one of the fastest growing food sectors worldwide. According to the FAO, there has been a 527% increase in global aquaculture production since 1990. By 2030, it is estimated that about two-thirds of all seafood produced for human consumption will come from aquaculture.

In addition to impacting wild fish stocks, climate change represents a major threat to global aquaculture. This is because most aquaculture farms consist of net pens or cages in the ocean, meaning that they are not protected from the damaging effects of climate change, such as warmer temperatures, increased acidity and reduced water oxygen content (hypoxia).



Dr Kurt Gamperl and his collaborators are investigating how climate change impacts fish physiology, in an effort to mitigate the impact of environmental stressors on both farmed and wild fish. Physiology is the study of how an animal's body functions and responds to its environment. In fish, it involves

One of Dr Gamperl's labs – the Laboratory for Atlantic Salmon and Climate Change Research.

A few members of Dr Gamperl's team.

measuring factors such as their stress response, heart function, oxygen consumption, and survival under a variety of conditions. This knowledge is essential for managing fish populations, especially in aquaculture farms.

Investigating how fish are affected by climate change is critical for improving the sustainability of aquaculture operations and informing effective conservation policies. 'Studying fundamental aspects of fish physiology can provide key information with importance for the conservation, survival and management of fishes,' says Dr Gamperl. 'It takes a highly integrative approach, and a large collaborative effort from all sectors, including academia, government, and industry to accomplish this.'

How Climate Change Impacts Fish Physiology

Climate change is predicted to increase global ocean temperatures by between 1°C and 3°C by the end of the 21st century – conditions that will be accompanied by low oxygen levels in the water. This is because oxygen is less soluble in warm water compared to cooler water, while the oxygen consumption of aquatic organisms increases with temperature. Such 'hypoxic' conditions may reduce the ability of many fish to adapt to the rapid warming caused by climate change. Coastal areas are also experiencing more severe and frequent heat waves, often at the same time as hypoxia. This means that many aquaculture farms, which are typically near the coast, may be more vulnerable to heat waves than previously thought.

Understanding the impacts of rising temperatures and the resulting low oxygen levels on fish physiology has been a central topic of Dr Gamperl's research. In recent years, substantial progress has been made towards understanding the cardiovascular system of many fish species, but little is known about how this system adapts to high temperatures or low water oxygen levels. Therefore, Dr Gamperl and his team set out find out.

The Sablefish

To do so, they studied a species called the sablefish, which is widely distributed along the North Pacific, and is considered to have extremely flavourful meat, rich in healthy oils. As these fish are incredibly efficient at converting feed into protein, and have a low environmental impact, they are now of interest as a species to farm.

Importantly, sablefish are very tolerant of hypoxia. To respond to warming waters, fish usually increase their heart rate to quickly transport oxygen through their blood. Dr Gamperl and his colleagues were the first scientists to investigate whether previous acclimation to hypoxic waters increases the ability of a fish species to respond to rapid warming.

Interestingly, for sablefish acutely exposed to hypoxic water, the team discovered that their heart rate did not increase, but unexpectedly dropped when the temperature was raised, and this limited their upper temperature tolerance and ability to survive. Further, even fish that had previously been acclimatised to hypoxia could not increase their heart function, leaving them vulnerable to the effects of increased temperatures.

These results show that living in hypoxic waters actually decreases the sablefish's ability to withstand heat waves, and that hypoxia can impair the heart's response to increased temperatures. The knowledge Dr Gamperl has gained on sablefish physiology will help formulate management policies for the species, towards developing sustainable aquaculture operations.

Investigating Atlantic Salmon

One of the most important farmed fish species is the Atlantic salmon. For salmon that are reared in cages in coastal waters, the most significant environmental challenge is high water temperatures combined with hypoxia during the summer. In one devastating incident in 2019, nearly 2.6 million farmed salmon off the coast of Newfoundland died. These deaths were largely attributed to a sustained period of high temperature (18–19°C) and a lack of oxygen as the fish crowded together seeking cooler water temperatures.

Sablefish. CREDIT: Dr Briony Campbell (GESF).

However, as part of the Mitigating the Impacts of Climate-Related Challenges on Salmon Aquaculture Project (MICCSA; see https://genomeatlantic.ca/feature-videos/), Dr Gamperl and his team have directly examined how increases in temperature, combined with moderate hypoxia, affect the behaviour and physiology of salmon. The team found that while salmon stop feeding at temperatures above 18°C, they can tolerate temperature up to 21°C, even when exposed to moderately hypoxic waters, and that fish in sea cages can survive such conditions. This research indicates that other factors must be present, in addition to temperatures of 18–20°C and hypoxia, for large numbers of salmon deaths to occur.

The team has also developed a number of biochemical assays and molecular markers to assess the health, welfare and environmental tolerances of salmon. 'This research can be used to assess fish health and to potentially select stocks that are more tolerant of environmental challenges,' says Dr Gamperl. 'This will be of great use to the salmon aquaculture industry, and potentially, to the culture of other fishes and the management of wild species.'

Coastal aquaculture farms will be increasingly affected by the changing environment. Therefore, the Atlantic salmon aquaculture industry will need to adapt to these changes to grow sustainably. The team's research will help enable the industry to recognise, and prepare for, the effects of warming and hypoxic coastal waters caused by climate change.

Insights into Cardiac Function

A similar species to salmon – the Arctic char – is an economically and culturally important fish for northern aboriginal peoples. This species is also making an increasingly important contribution to aquaculture in Canada and Europe. However, many experts are concerned about the ability of this species to tolerate rising temperatures. Dr Gamperl's team has provided key insights into why Atlantic salmon are more tolerant of high water temperatures than Arctic char, and why char populations are especially vulnerable to climate change.

Cardiac performance, such as maximum heart rate and pumping capacity, are lower in char than salmon, and these differences in cardiac performance may make it more difficult for char to tolerate warmer temperatures. Impaired cardiac performance in fish can negatively impact swimming, foraging and migration, and ultimately reduce survival.

To better understand how the fish heart responds to high temperatures, the team also studied the function of mitochondria in the heart muscle cells of salmon. Mitochondria, the powerhouses of cells, are present in large numbers and are required to meet the high energy demands of the beating heart.

In their study, the researchers acclimatised one group of salmon to a temperature of 12°C and a second group to 20°C. They found that salmon that had been acclimatised to the warmer temperature had improved mitochondrial function when they were exposed to higher temperatures of up to 26°C. Further, they report that less efficient mitochondrial and heart function likely contribute to the reduced heat tolerance of char.

These fascinating insights into heart and mitochondrial function enhance our understanding of how salmonids, including salmon, trout and Arctic char, will respond to climate change. Dr Gamperl's research will undoubtedly aid in the development of improved regulations and conservation measures to protect Arctic char.

A Work in Progress

Dr Gamperl team's future plans include using an integrative approach to examine how maximum oxygen consumption, heart function and blood oxygen transport differ between marine fish species and how these physiological characteristics allow them to acclimatise to their environment. They will continue to study the physiology of fish with the goal of understanding how evolution has shaped the physiological systems of fish and whether fish are likely to adapt to the effects of climate change.

Collaboration across all sectors will continue to be critical in tackling the many challenges that climate change poses to both farmed and wild fish populations. Dr Gamperl's innovative research into fish physiology and biology has raised many new and exciting questions, and will continue to have important implications for fish conservation and ensuring global food security in the face of climate change.

Meet the researcher

Dr Kurt Gamperl
Department of Ocean Sciences
Memorial University of Newfoundland and Labrador
St. John's, Newfoundland and Labrador
Canada

Dr Kurt Gamperl earned his PhD in Biology at Dalhousie University, Nova Scotia, in 1994. He was an Assistant Professor of Biology at Portland State University before moving to Memorial University of Newfoundland and Labrador, where he is now a Professor in the Department of Ocean Sciences. Here, he is also the Associate Director of the Ocean Sciences Centre. Dr Gamperl's integrative research program focuses on understanding how environmental and physiological variables interact to affect fish biology. His internationally recognised research has led to over 125 publications in peer-reviewed journals and over 35 research grants. In addition to his research, he teaches courses in fish biology, animal physiology and aquaculture, and supervises many graduate and undergraduate students, post-doctoral researchers and research assistants.

CONTACT

E: kgamperl@mun.ca
W: https://www.mun.ca/osc/kgamperl/bio.php

KEY COLLABORATORS

Dr Brian Dixon, University of Waterloo
Dr Doug Syme, University of Calgary
Dr Matthew Rise and Dr Javier Santander, Memorial University of Newfoundland and Labrador
Dr Ken Rodnick, Idaho State University
Dr Mark Fast, University of Prince Edward Island
Dr Roy Danzmann, University of Guelph
Danny Boyce, The Dr Joe Brown Aquatic Research Building, Memorial University of Newfoundland and Labrador
Dr Amber Garber, Huntsman Marine Science Centre
Jessi Rix, Somru BioScience
Dr Briony Campbell, Golden Eagle Sable Fish
Dr Andrew Swanson, Cooke Aquaculture
Dr Laura Braden, AquaBounty Canada Inc.

FURTHER READING

AK Gamperl, ZA Zrini, RM Sandrelli, Atlantic salmon (*Salmo salar*) cage-site distribution, behaviour and physiology during a Newfoundland heat wave, Frontiers in Physiology, 2021. DOI: 10.3389/fphys.2021.719594

AK Gamperl, DA Syme, Temperature effects on the contractile performance and efficiency of oxidative muscle from a eurythermal vs. a stenothermal salmonid, Journal of Experimental Biology, 2021, 224, jeb242487. DOI: 10.1242/jeb.242487

A Beemelmanns, FS Zanuzzo, RM Sandrelli, ML Rise, AK Gamperl, The Atlantic salmon's stress- and immune-related transcriptional responses to moderate hypoxia, an incremental temperature increase, and these challenges combined, G3: Genes, Genomes, Genetics (Bethesda), 2021, Apr 7. DOI: 10.1093/g3journal/jkab102.

RHJ Leeuwis, FS Zanuzzo, EFC Peroni, AK Gamperl, Research on sablefish (Anoplopoma fimbria) suggests that limited capacity to increase heart function leaves hypoxic fish susceptible to heat waves, Proceedings of the Royal Society B, 2021, 288, 20202340.

AK Gamperl, OO Ajiboye, FS Zanuzzo, RM Sandrelli, EFC Peroni, A Beemelmanns, The impacts of increasing temperature and moderate hypoxia on the production characteristics, cardiac morphology and haematology of Atlantic Salmon (*Salmo salar*), Aquaculture, 2020, 519, 734874.

L Gerber, KA Clow, FC Mark, AK Gamperl, Improved mitochondrial function in salmon (*Salmo salar*) following high temperature acclimation suggests that there are cracks in the proverbial 'ceiling', Scientific Reports, 2020, 10, 21636.

MEMORIAL UNIVERSITY