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CULTIVATING SUSTAINABLE FOOD SECURITY & BIODIVERSITY

HIGHLIGHTS:

- Building Community Resiliency through Horticultural Innovation
- Microbes: Agriculture's Microscopic Helpers
- Regenerative Agriculture: Putting the Heart and Soul Back in Farming
- Human Elements of Pollinator Conservation

EXCLUSIVES:

- The Canadian Association for Food Studies
- The British Society of Soil Science

Issue: #134

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WELCOME...

While the world's attention is focused on eradicating COVID-19, we must not forget that unsustainable farming practices and the ensuing biodiversity declines were leading factors in the emergence of this devastating disease. To prevent future pandemics, we must now find new ways to feed the human population while also protecting and restoring Earth's biodiversity. Such sustainable agricultural methods have a range of other positive impacts, including climate change mitigation, improved animal welfare, and reduced social inequality.

In this important edition, we meet researchers who strive to improve food production, and those who are finding new ways to boost biodiversity, towards a healthy, equitable and sustainable future for all of Earth's inhabitants.

Our first section in this edition showcases research that seeks to develop fairer food systems. From helping family-run farms in the US to survive in the face of competition from industrialised farms, to developing nutritious baby food from a local and affordable yam in Cameroon, this section highlights a range of inspiring initiatives.

Next, we introduce scientists who develop eco-friendly farming practices that can keep up with the demands of a growing human population. In this section, we meet scientists who are working to reduce our reliance on toxic agrochemicals, and others focusing on how to improve soil health, so that biodiversity can thrive alongside our crops and livestock.

Our final section highlights the work of several pioneering ecologists. Here, we feature a selection of promising projects – from predicting the future of Puerto Rico's forest ecosystems, to investigating landowners' attitudes towards pollinator conservation, all with the aim of informing new strategies and programs that protect and restore Earth's precious biodiversity.

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

Meet The Team...

DIRECTOR
Nick Bagnall
nick@sciencediffusion.com
EDITOR-IN-CHIEF
Dr Nelly Berg
nelly@sciencediffusion.com
EDITOR
Dr Catherine Deeprose
catherine@sciencediffusion.com

DESIGN MANAGER
Mimi Jones
PUBLICATION MANAGERS
Tom Render
tom@scientia.global
Paris Allen
paris@scientia.global
Mike King
mike@scientia.global
James Phillips
james@scientia.global

CONTRIBUTING WRITERS
Kelleigh Greene, MSc
Sarah Wilkinson, BSc
Stephanie Rose, PhD
Lynne Holmes, BSc

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FOOD EQUITY: BUILDING FAIRER FOOD SYSTEMS FOR ALL

Our first section in this edition showcases research that strives to develop fairer food systems – from growing food to processing, purchasing and eating it – towards ensuring equitable food security into the future.

In the face of increasing agricultural industrialisation, which often serves to accelerate inequality, we look at ways to keep family farmers on their land, enabling them to provide their local communities with affordable, fresh and healthy produce. We also feature research that seeks to get the most out of local and affordable crops, towards ensuring that children have adequate nutrition.

To open this section, we feature an exclusive interview with Dr Amanda Wilson, President of the Canadian Association for Food Studies. Here, Dr Wilson describes how the Association facilitates interdisciplinary research that seeks to develop fairer and more equitable food systems.

Our second article highlights a remarkable initiative called the HoChunk Harvest Project, coordinated by Vincent Bass, former member of the HoChunk Tribal Council, and Brian Mathers of the HoChunk Community Development Corporation. By reconnecting people with the land, this project maximises the use of local resources to produce healthy, sustainable, and culturally appropriate food, towards the ultimate aim of achieving food sovereignty for the HoChunk people in Winnebago.

Next, we meet Dr James Simon of Rutgers University and his colleagues, who have developed a unique horticulture model that trains people on agribusiness and technical skills, particularly women and youth in sub-Saharan Africa. This model has evolved over 20 years in several countries including Ghana, Senegal, Kenya and Zambia, where it has helped local people to successfully develop sustainable businesses centred on the cultivation of traditional indigenous crops.

Meanwhile, in the US, transitioning to the cultivation of traditional ethnic crops could help struggling farmers to break into a growing market, while also helping to fulfil the needs of African, Asian and Hispanic communities. Here, we meet Dr Ramu Govindasamy from Rutgers University, who uses a market-first approach to investigate and develop opportunities for family farmers to make the shift to ethnic crop production.

Also helping family-run farms to survive in the face of increasing competition from industrialised farms is Dr Thomas Gray of the Rural Business-Cooperative Service at the US Department of Agriculture (USDA). Through the 'Agriculture of the Middle' Initiative, Dr Gray and his colleagues have been studying different types of cooperatives that could help these farms to survive and thrive. By identifying the 'federated cooperative' as the most beneficial organisational structure for family farms, this project could lead to a range of positive effects in rural communities, since incomes, education levels and numbers of local businesses all tend to be greater in communities surrounded by small to medium farms, compared with those surrounded by industrialised farms.

Next, we return our attention to indigenous African vegetables, focusing on a nutritious yam called *dioscorea schimperiana.* Here, we meet Dr Marlyse Leng and her colleagues at the University of Douala in Cameroon, who have recently developed a nutritious baby food from this endangered yam species, to increase its production and use, while also addressing childhood malnutrition. After processing the yam with other key nutrients into an optimised formulation, they explored the food's nutrient availability and antioxidant activity. Dr Leng and her team hope that their affordable, sustainable and locally produced baby food will soon be available on the market, towards combating malnutrition in Cameroon and beyond.

Continuing on the theme of nutrition, our final article of this section showcases the research of Dr Lisa Dean and her team at the USDA's Agricultural Research Service, who have been investigating the flavours, nutritional compositions and physical properties of peanuts, with the aim of enhancing their quality and usage. Because of their high nutrient density, environmental benefits, affordability and culinary versatility, peanuts are seen as key to ensuring global food security into the future.

THE CANADIAN ASSOCIATION FOR FOOD STUDIES

The Canadian Association for Food Studies allows researchers from diverse disciplines to meet regularly to share their findings and collaborate on diverse issues relating to food systems. In this exclusive interview, we speak with CAFS President **Dr Amanda Wilson**, who describes how the Association facilitates interdisciplinary scholarship in the areas of food production, distribution and consumption, towards addressing social, environmental and economic challenges within our food systems.

To begin, please give us a brief introduction to CAFS. Why was the Association founded?

The Canadian Association for Food Studies is an academic association that promotes critical, interdisciplinary scholarship in the broad area of food systems: food policy, production, distribution and consumption.

It was founded in 2005 by a group of academics and community-based researchers, following a conference on food security. They had identified a need for an association that would bring together scholars from diverse disciplines and backgrounds to share research, learn from each other and collectively identify research priorities moving forward. While CAFS first emerged in response to questions of food security, it has since expanded to include a range of food systems concerns and challenges – everything from food policy, to critical dietetics, food cultures, food literacy and alternative food networks.

Can you give a few examples of the types of research that your members conduct?

The types of research that members conduct is really quite diverse.

One example is a project called FLEdGe (Food: Locally Embedded, Globally Engaged), which is a multi-year research project exploring opportunities to build transformative and sustainable food systems. Working in partnerships with a range of community-based organisations, researchers have identified six 'Good Food Principles', and have produced a range of case studies illustrating these principles in practice.

Another is the Family Farms and Work project, which examines the experiences and policy context of non-wage household workers on Alberta farms, highlighting the tensions and complexities involved in health and safety within the context of family farms. The research involves interviews with farm operators and family members, as well as workers and government regulators, combined with a policy and document analysis.

Feeding the City is a community-based research project seeking to understand how a range of food actors are affected by, and responding to the COVID-19 pandemic. Drawing on both qualitative and quantitative data, researchers hope to highlight not only the challenges but the resilience of local food systems in the face of crisis.

While these projects demonstrate the breadth of research conducted by CAFS members, it also highlights some commonalities – collaborative research and a commitment to addressing pressing social, environmental and economic challenges within our food system.

Why is studying food and food systems from these perspectives now more important than ever before?

Well, I would argue that studying food and food systems has always been important, but certainly there is a growing recognition of the crucial role played by food and food systems in relation to our environment and climate change, public health, social inequities as well as culture and identity.

'It sounds cheesy, but CAFS really is a welcoming community – I think if you asked members what they value most about their involvement in CAFS, they wouldn't just say networking or meeting individual people, but the sense of being a part of a broader whole, a collective of people who, together, provide a constructive and supportive space for learning and reflection.'

As an association that brings all of these different facets and questions together, it helps us understand the connections between them – what is often referred to as a food systems perspective. Given the current challenges that our society is facing, food has emerged as a really important lens though which to not only better understand those issues and their implications, but take concrete actions to change them.

How does CAFS promote collaboration between researchers in similar and disparate research areas?

Food studies, by its very nature, is interdisciplinary, so we definitely see research in multiple fields. However, I think it is fair to say that the majority of our membership is situated within the social sciences and humanities, using predominantly qualitative research methods.

In the past couple of years, due to member interest, we've established a protocol for the creation of research Working Groups within CAFS. The idea behind these Working Groups is to facilitate collaboration and communication among scholars working on a common topic. At the moment there is one active Working Group, on School Food. The goal of this Working Group is to promote the best available evidence for the development of a national school food program. So, these research groups are one way for researchers from different backgrounds to come together and collaborate on a common topic.

During our annual conference, we also seek out opportunities to collaborate with other academic associations. For instance, in the past we've co-organised sessions with the Canadian Communications Association and the Canadian Sociological Association. These joint-sessions help to establish links and connections across disciplines and fields of study.

Who makes up the current membership of CAFS? Aside from the Working Groups and Annual Conference, what are the other benefits of being a member?

We have approximately 200 members, made up of faculty, students as well as community practitioners and community-based researchers. A core element of CAFS, since its very beginning, has been strong connections with practitioners and civil society organisations. CAFS isn't strictly an academic space, it's a space where faculty, student and practitioners connect and learn from one another.

I think one of the real values of CAFS is the space for constructive dialogue and learning. We have a very active Listserv which is used not only to share information, but to engage in conversation and discussion about contemporary issues. Just the other week there was a lively thread discussing the merits and framing of basic income strategies.

We also have a quarterly newsletter which promotes not only the activities of the association, but research and publications of our members. We've also launched a webinar series this year; the first one explored Indigenous perspectives on the place of 'Canada' in Canadian Food Studies, and the second is a conversation between two food scholars on the state of critical agri-food studies.

Finally, CAFS also houses the Canadian Food Studies journal, a peer-reviewed, open-access interdisciplinary journal showcasing critical scholarship on the diverse dimensions of the foodscape in so-called Canada.

It sounds cheesy, but CAFS really is a welcoming community – I think if you asked members what they value most about their involvement in CAFS, they wouldn't just say networking or

meeting individual people, but the sense of being a part of a broader whole, a collective of people who, together, provide a constructive and supportive space for learning and reflection.

Describe the role that food studies can play in demonstrating the unequal social and environmental impacts of food systems, and how these studies can inform policies that promote social transformation.

As an academic association, our primary purpose is to provide a space of critical dialogue and learning for our members. However, I believe we are also a group of scholars committed to using our research to advance more just and equitable food systems; with that comes a responsibility to speak out against injustices and a commitment to follow-through with action.

Food studies research has helped to exposed the many challenges facing our food system; but it also highlights proposed solutions and alternative to those problems. For instance, the federal government went through a process to develop a national food policy for Canada a couple years ago. Many CAFS members were very active in the consultation process – providing evidence, analysis and policy proposals to steer this national food policy in the right direction.

I think there has always been a recognition within food studies that research is not merely an objective, neutral exercise. Research is not immune to the broader systems and structures of power found within society; asking particular questions, pursuing particular lines of inquiry can reproduce or challenge those relations of power in different ways.

Academia – academic institutions and organisations, including CAFS, are not immune to the injustices found within society as a whole. This year the CAFS board has made a series of commitments to taking concrete actions to challenge systemic anti-black and anti-Indigenous racism within our food system and society. This first came about in the Summer, in response to the waves of protests and resistance movements against racialised police violence (read our statement here).

More recently, our association issued a statement in support of Mi'kmaq fishers in Nova Scotia, who were exercising their treaty rights to fish for a moderate livelihood, and were met with violence and opposition from white fishers in the area (read our full statement here). As a board, we believe it is important for academic associations to contribute to contemporary conversations that have direct bearing on our food systems – that we have a responsibility to make use of the research and analysis we've developed and co-constructed to improve our society.

Finally, how have the Association's activities been affected by the COVID-19 pandemic? How might the pandemic impact the field of food studies in general?

Like many academic associations, we have moved our upcoming annual conference entirely online. We also made the decision last year to cancel our annual conference, rather than move it online. We just didn't feel like we had enough time and space to re-vision the conference we had been planning all year.

Not having an in-person conference is a real loss for CAFS members – given that many of us are quite geographically spread out, it's one of the only opportunities for members to see each other in-person, get to know new members etc. Replicating those informal connections and conversations is difficult in an on-line conference, but It's often what people value most about these events – that sense of community. We're planning a joint virtual conference this Spring, with our counterpart associations in the United States, which will create different kinds of opportunities for connection and collaboration.

The pandemic has really underscored and accentuated many pre-existing problems in our food system – rates of food insecurity, inadequate food governance mechanisms, corporate concentration, the precarity of food workers, and in particular the exploitation of migrant farm workers. These problems feel pretty daunting, but I've been impressed by how quickly CAFS members, and food scholars in general, have taken to not only documenting these issues, but actively working with community partners to address them. Food scholars have pivoted to tackle these pressing needs, building on existing research expertise and relationships to help us better understand the impact of this pandemic on our food system, and help to ensure our food system emerges from this pandemic more resilient and sustainable.

On the other hand, the pandemic has also put a real strain on many of our members, particularly those with caring responsibilities, or those with underlying health conditions. Planned data collection activities has been postponed, conference opportunities delayed or re-worked, not to mention the added workload of switching to online teaching. I think it's fair to say that it will be a difficult year for many of our members.

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L'Association canadienne des études sur l'alimentation
Canadian Association for Food Studies

THE HOCHUNK HARVEST PROJECT: RESTORING SUSTAINABLE FOOD SOVEREIGNTY

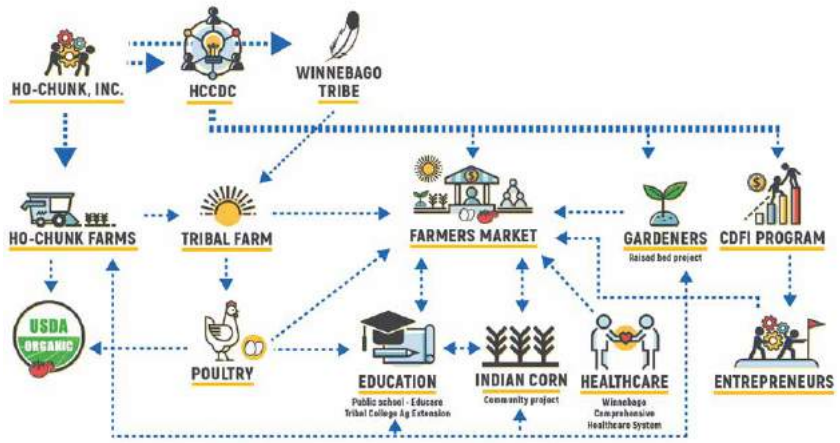
The HoChunk people of the Winnebago Tribe of Nebraska traditionally enjoyed a close connection with their environment, which has gradually become fractured due to increased urbanisation. The community has become reliant upon external producers for nearly all of its food requirements, and the health of its members is suffering as a result. In an effort to reconnect people with the land, a project coordinated by former Tribal Council member, **Vincent Bass**, and **Brian Mathers** of the HoChunk Community Development Corporation, aims to maximise the use of local resources to produce healthy, sustainable, culturally-appropriate food. Their ultimate goal is to achieve food sovereignty for the Winnebago Tribe.

A Food System Out of Balance

The HoChunk are a Native-American people whose historic territory includes parts of Wisconsin, Minnesota, Iowa, and Illinois. Today, HoChunk people are enrolled in two federally recognised tribes – the Ho-Chunk Nation of Wisconsin and the Winnebago Tribe of Nebraska. The Nebraska Tribe's reservation in Thurston County, in north-east Nebraska, is home to 2893 residents, two-thirds of whom are Native American. The reservation is entirely rural, and its four-year average poverty rate is 28.9% – more than double Nebraska's state-wide average.

As a geographically isolated and disproportionally low-income tribal community, the Winnebago Tribe's food system is challenged by many factors. The residents living on the reservation have no full-service grocery store in the community – the nearest is located eighteen miles away in the Sioux City metropolitan area. Many low-income households have transport barriers, and so rely on Winnebago's two convenience stores for their food supply. These are expensive shopping options and have hardly any fresh produce for sale. The community runs meal programmes for low-income people; however, these are unable to integrate fresh or locally grown foods into their menus because of the dearth of nearby growers with established local commercial delivery pipelines.

As well as being hunters and gatherers, historically the HoChunk people of the Winnebago tribe were also food growers – eating food when it was in season and living a healthy life in harmony with their surroundings. With increasing urbanisation and changing lifestyles, this connection to the land has been eroded, and very few households on the reservation have been engaged in



Interrelationships between the project components, the groups that are part of it, and community elements

gardening or growing. In fact, nearly 100% of food consumed by reservation residents is grown off-reservation. This reliance on external suppliers threatens the Tribe's food sovereignty, their right to healthy and culturally appropriate food produced through ecologically sound and sustainable methods, and the ability to define their own food and agriculture systems.

These factors are also having a cumulative detrimental effect on the health of the Winnebago tribal population, who suffer disproportionately from a number of serious conditions related to nutrition, including obesity, hypertension and diabetes. One third of children under four years old in Winnebago's Women, Infants and Children program are already clinically obese, with an additional 16% being overweight. Nearly three-quarters of adults are an unhealthy weight (72%) and more than half of hospital admissions are for patients with diabetes.

There is a general recognition within the community that the current fractured food system is out of balance, and in 2015 the Winnebago Tribal Council initiated community planning and organisation around food sovereignty, forming the Winnebago Food Security Task Force. Consequently, the HoChunk Harvest Community Food Project was born, administered by the non-profit HoChunk Community Development Corporation (HCCDC), along with a broad coalition of local stakeholders. The project is led by former Tribal Council member, Vincent Bass, and HCCDC's Executive Director, Brian Mathers, and aims to implement key components of the Task Force's comprehensive food sovereignty plan.

'Our vision is that members of the Winnebago Tribe of Nebraska are able to meet their own food and nutrition needs,' says Bass. 'We're looking for ways that we can maximise tribal land, water and human resources, to produce local food that is healthy, sustainable, culturally meaningful, and widely available to all residents of the reservation.'

Utilising Local Resources to Meet Community Needs

Food security is complex and multifaceted, and the HoChunk Harvest Project group recognised that meaningful progress on a number of levels, including local food production, community education and economic development, would need to occur in tandem for the project to be successful. 'For this reason, we set up a number of integrated initiatives,' says Mathers. 'Our approach has been supported and enhanced by the collaborative relationships of the many community partners involved.'

The interrelationships between the project components, the groups and organisations that are part of it, and the elements of the community that are impacted by the project, are clearly illustrated by the local food systems diagram featured in this article, produced by the food sovereignty team.

To address the recent cultural and social shift away from the land, and to get families growing again, one of the initiatives introduced was a Raised Bed Home Gardening project. 'We've targeted low-income households, elderly individuals and families with children,' explains Bass. 'We've provided them with a raised bed structure, topsoil, hand tools, seedlings and seeds – everything they need to start growing their own produce at home.'

To increase the likelihood of continued gardening, project partners HoChunk Farms and Little Priest Tribal College provide help and instruction for first-time gardeners. In addition, participants are linked with a nutritionist from the Tribe's Health Department, who provides seminars and cooking classes to demonstrate how to prepare the produce grown. An annual Harvest Festival is conducted to celebrate harvest and generate further community interest. So far, the initiative has engaged nearly 200 new households in growing their own food.

One of the most visible outcomes of the HoChunk Harvest Project has been the construction of a 'Village Market' structure in HoChunk Village – adjacent to the major traffic thoroughfare in the county. More than 300 people – primarily low-income and elderly Native Americans – live within walking distance of the new building. The Village Market has space for thirty vendor booths and also houses the tribal college's agricultural extension office. A weekly farmers' market is now held during the growing season, where growers are asked to donate unsold produce at the end of the market day for local senior meals and children's feeding programs.

In terms of further increasing the tribe's ability to develop business opportunities and reduce reliance on external suppliers, one project partner, HoChunk Community Capital Inc, is working with new food and agriculture-related business start-ups to develop business plans, solidify credit scores, explore market niches and launch businesses. Alongside delivering one-on-one assistance, HoChunk Community Capital coordinates business training and seminars from other partners including Little Priest Tribal College and Briar Cliff University. The organisation has also made $50,000 in start-up capital available to small agricultural businesses that are ready to launch or expand.

Through this process, the HoChunk Harvest Project has started to connect fledgling local growers with the resources they need to explore the feasibility of replacing low-wage work with sustainable small businesses, or supplementing household incomes through sale of produce or value-added food products.

A Healthier Future

The initiatives run as part of the HoChunk Harvest Project represent a holistic approach to increasing local food production and improving community health. The Project provides opportunities to increase use of available land to address food needs, engages more tribal members in growing their own food and integrating it into healthier diets, and creates entrepreneurial and economic development opportunities.

Mathers is keen to point out that the HoChunk Harvest Project is just the beginning. 'We're merely planting the seeds for prolonged and sustainable growth,' he says. 'These initiatives are all part of the Tribal Council's long-term vision of building the community's self-reliance.' Indeed, all of the elements of the Harvest Project are designed to have a useful and lasting legacy.

The raised gardening beds will last long beyond the project lifespan, the Village Market is a permanent installation and long-term asset, and the business models that have been developed will keep people employed on the reservation and provide opportunities for future generations. With increased availability of healthy, locally produced food, Mathers also hopes that the community will start seeing the positive impacts on their health, and consequentially, reduced pressure on healthcare services.

Projects running alongside the HoChunk Harvest Project will further support the community's goal of food sovereignty. Another aim of the original Task Force was to establish genetically pure varieties of the Tribe's traditional corn and build up a sustainable supply for this and other food plants important for nutrition and ceremonial use. The Tribe and HoChunk Farms have also been working with St. Louis Zoo's Centre for Native Pollinator Conservation to source heirloom corn, beans and squash seeds. In 2017, they planted a five-acre parcel in Winnebago with 'Johnson County White' corn, and also donated seed to neighbouring tribes. The harvested corn was used in corn soup for senior citizens, as well as at memorials and funerals.

Other initiatives are also underway, including increasing habitat to support pollinators, and converting tribal land currently leased for corn, soybean and livestock feed production to organic food production for local consumption. The Little Priest Tribal College has also been awarded Tribal College Extension Program funding through the USDA National Institute of Food and Agriculture, to expand efforts to increase agriculture, health and natural resources literacy for all residents of the Winnebago Indian reservation.

'We're already seeing the benefits of increasing our community's connection with the land,' says Bass. 'It's rewarding to see the positive impact that our collaborative effort has had on the health, wellbeing and identity of the community, as well as the environment in which we live. These are useful first steps to but there's still work to be done. We must continue to build on our achievements so far and work towards our long-term aim of establishing food sovereignty for the Winnebago tribe, with all of its associated benefits.'

Meet the researchers

Brian Mathers
Executive Director
HoChunk Community Development Corporation
Winnebago, NE
USA

Brian Mathers has more than 20 years' experience managing service programs for high-need communities. He is currently Executive Director of the HoChunk Community Development Corporation (HCCDC) – a non-profit community development agency focused on improving economic opportunities and quality of life for tribal communities. During his previous tenure as Executive Director of the Lincoln (Nebraska) Action Program, he administered two successful multi-year USDA-funded Community Food Projects. Mathers has also held the position of President/CEO at the Center for Siouxland – a non-profit human service agency, as well as working for several years as Director of Research Development at the University of South Dakota. He holds a Bachelor of Arts in Psychology and Speech from Buena Vista University, Storm Lake, Iowa.

CONTACT

E: bmathers@hccdc.org
W: www.hccdc.org

Vincent L. Bass
HoChunk Harvest Coordinator
HoChunk Community Development Corporation
Winnebago, NE
USA

Vincent Bass is a Winnebago Tribe of Nebraska elder who has served his community in various tribal governance and enterprise capacities over the past three decades. In addition to serving thirteen years as a Winnebago Tribal Council member, Mr Bass has worked to develop and sustain tribal enterprise initiatives focused on gaming and product distribution. Mr Bass's leadership on the Tribal Council was a key factor in the Tribe's pursuit of food sovereignty. He has an Associates Degree in Building Construction from Northeast Nebraska Technical College.

CONTACT

E: vbass@hccdc.org
W: www.hccdc.org

KEY COLLABORATORS

Aaron LaPointe, tribal member and CEO of HoChunk Farms
Lorelei Decora, Winnebago Public Health Department
Dr Ed Spevak, St Louis Zoo
Janyce Woodward, Little Priest Tribal College
Monica Cleveland, Tribal Office of Environmental Health

FUNDING

USDA – Community Food Projects Competitive Grant Program (CFPCGP)
Winnebago Community Development Fund
Ho-Chunk, Inc. (Winnebago, NE)
Native American Agriculture Fund
Peter Kiewit Foundation (Omaha, NE)
Cooper Foundation (Lincoln, NE)
Nebraska Rural Business Development Grant (USDA)

BUILDING COMMUNITY RESILIENCY THROUGH HORTICULTURAL INNOVATION

Food insecurity directly impacts a third of the world's population and perpetuates a cycle of hunger and malnutrition that is inherited through generations. Previous relief efforts have largely been donor-focused, providing only temporary solutions. To break the cycle of food insecurity, poverty, and hunger, relief efforts must empower communities and facilitate real transformative changes. **Professor James Simon** of Rutgers University and colleagues have developed a transferable horticulture model that builds upon local ecosystem knowledge and cultural infrastructures while embedding science-driven, market-first, and value chain methodologies. Introduced into several countries in sub-Saharan Africa, the model includes agribusiness and technical skills training to strengthen the participation of farmers and local entrepreneurs, particularly women and youth, in profitable value chains. Using this novel approach, the Rutgers team and their African colleagues have successfully demonstrated how horticulture can contribute to a real reduction in poverty and malnutrition, while fostering job creation, pride and creativity.

Vicious Cycle of Poverty and Malnutrition

At least 820 million people are hungry today. Tomorrow they will be hungry again, and again the day after that. The relentless daily hunger experienced by one in seven people worldwide is inextricably linked with poverty. Of the world's 7 billion people, 37% live on less than $2 USD per day. Families already struggling to adequately feed and nourish themselves have little hope of gathering additional resources to break the cycle of poverty and hunger that is passed down through generations.

In 2010, the Food and Agriculture Organization estimated that of the 925 million malnourished people across the globe, 239 million (over one quarter) are from sub-Saharan Africa. According to the World Bank, the number of people living in poverty in the region increased from 278 million in 1990 to 413 million in 2015. Continued population growth and worsening agricultural productivity – owing to the pressures of climate change – are likely to further exacerbate poverty, hunger, and malnutrition.

The Need for Innovative, Community-Based Solutions

Tackling today's complex food systems challenges must begin by understanding the social, cultural, and environmental infrastructure and local knowledge of the communities in need.

Prior to the Colonial disenfranchisement, indigenous communities throughout the world evolved complex agricultural practices that were uniquely suited to supporting

Growers greatly benefit from solar panels that power irrigation pumps and electric fences protecting crops from elephants and other animals.

populations and associated cultures within the limits of their local ecosystems. Historically, conventional food aid programs administered by industrialised countries with the intent of providing immediate help too often ignored local knowledge and traditional practices.

This top-down approach reduced hunger and malnutrition through the immediate provision of food and other relief, but often only temporarily. Without analysing a community's complexity and addressing local obstacles preventing people from becoming self-sufficient and independent, communities remain locked in cycles of poverty that reduce their future resilience.

Significant international aid provides massive immediate relief, with staple crops providing the energy, protein, and

Growers harvest African Birds Eye Chili in southern Zambia where fruits are dried, graded, sorted and sold to local and regional markets.

carbohydrates to satiate large and vulnerable populations. However, the underlying issues that lead to crisis and the need for humanitarian relief are often not resolved or addressed.

Furthermore, the dependence on foreign crops and foreign agricultural methods may not always be appropriate for the climate and environment of sub-Saharan Africa. The intensive agricultural practices that would be required to produce some temperate-zone crops could, in some cases, make these food crops largely unsustainable and prohibitively costly, limiting their long-term efficacy.

Conventional foreign aid, while providing many benefits, may also come with negative social outcomes for many developing communities. Internalised oppression lingers from the days of colonial rule, the psychological effects of which include a negative view of traditional cultural practices such as indigenous agricultural and traditional foods and a lack of perceived value on native and indigenous plants, simply because they are not part of the larger-scale commercial agricultural industry. Integrating traditional agricultural knowledge into food system interventions and practices can inspire long-lasting positive behavioural changes.

Horticulture for a Better Future

The enormities of today's food security challenges require innovative, sustainable, place-based solutions.

New nutritional and economic strategies that are sensitive to the unique, local knowledge, as well as the challenges facing developing communities across sub-Saharan Africa, are desperately needed. Long-term improvements require a holistic approach that tackles the root causes of poverty and malnutrition, while inspiring pride in local and sustainable agricultural practices. Recognising this major challenge, the United States Agency for International Development (USAID) produced an ambitious multi-sectoral strategy for 2014–2025 to decrease malnutrition, improve nutrition, and increase economic productivity.

Horticulture, focusing on the cultivation of local and indigenous fruits, vegetables, flowers, and medicinal crops, has the potential to form the basis for the ambitious nutritional and economic strategies that support USAID's objectives. Since 70% of the world's extreme poor live in rural areas, and most are farmers, strategies that focus on culturally based agri-business have the potential to capture many of the most vulnerable communities.

Horticultural crops are ideal for efforts to improve nutritional and economic outcomes. A diverse diet including at least 400 grams of fruits and vegetables daily can prevent malnutrition, due to their high vitamin and mineral content. Horticultural crops can provide these important micronutrients without excessive calories, mitigating the risk of hidden hunger. Preventing malnutrition during the early years of childhood supports development and lifelong optimal health, which can benefit and improve the resilience and wellbeing of communities for decades.

Agronomists drying African Indigenous Vegetables using a solar dryer. CREDIT: David Byrnes.

Through years of research and refinement, Professor James Simon and a team of researchers from Rutgers University in collaboration with African colleagues have developed a comprehensive model that is transforming the agricultural landscape for communities across sub-Saharan Africa. With horticulture at its core, their strategy focuses on identifying and building opportunities from the bottom-up, by empowering communities to take charge of their own social, cultural, environmental, and economic futures.

The team's first focus was on African botanicals, which include under-utilised and under-recognised herbs, spices, nuts, plant-based butter, and medicinal plants. To some, these were mere 'boutique crops' and therefore not largely recognised by commercial enterprises; however, for the communities involved in collecting or growing and harvesting such plants, these crops demonstrated how under-utilised local plants could contribute to food security and improved nutrition.

This iterative model began to incorporate a strong focus on indigenous horticultural crops, including African indigenous vegetables. These plants, which exhibit general climate change resiliency and are well suited to the growing conditions in sub-Saharan Africa, were identified by way of community surveys to be a preferred food choice, but were generally unavailable.

Traditional indigenous crops, as well as novel indigenous food plants, have amazing potential to combat malnutrition while generating jobs and income. Scientific evaluations have already demonstrated many health and nutritional benefits that these plants can provide, including high antioxidant capabilities, and excellent phytochemical and bioactive profiles.

Such foods have great market potential from local to regional and international levels. Building success with indigenous horticultural crops can improve social outcomes by fostering a sense of cultural pride and belonging. A focus on these indigenous crops can contribute significantly to overcoming hunger and improving nutrition, and create income generation opportunities for women and youth.

Horticultural strategies have the potential to target some of the most marginalised groups. Many of the individuals included in the team's projects in sub-Saharan Africa are women, single-parent families and the elderly, as well as populations that are re-building after war and other crises. Empowering previously marginalised groups benefits not only those individuals but also stimulates the local economy, thus benefiting the entire community.

Importantly, families do not stop cultivating traditional staple or commodity crops to begin cultivating horticultural crops. Rather, the higher-value crops are introduced and promoted as additional crop enterprises, and are not intended to replace the families' and communities' core staple crops. Farming small plots, such as gardens, is possible alongside traditional crops. This can significantly improve food security, because year-round production is possible with adequate watering. Daily water collections from natural waterways can eventually be replaced with gravity-controlled irrigation systems, water collection systems and others that are simple and easy to install.

Horticulture can be a particularly lucrative endeavour; in comparison to traditional commodity crops, horticultural fruits and vegetables obtain a higher price. The additional income from selling high-value horticultural crops can help support improvements in infrastructure and education. Freed from the daily struggle of survival, communities of well-nourished, healthy people with some money to spare can begin focusing on building a better future for themselves.

Community-Based Science and Market-Driven Approach

Professor Simon's model takes a three-pronged systems approach to a complex problem, beginning by building upon indigenous agricultural practices, reinforced by science and new technologies, and sustainably developed for the market to ensure economic resilience. The model focuses on 'the four As': Access, Availability, Affordability and Adoption of all the crops targeted in consumer and market demand.

Rather than using a production-based approach, the team uses a market-first paradigm, which from the outset, identifies local community champions and leaders from the private and public sector that can form strategic partnerships with communities. These local leaders are included at the onset so that they actively participate in shaping their horticultural enterprises and develop their technical and leadership skills to sustain the food system long after the project ends.

Women using a tool to more efficiently and quickly remove the seeds from hibiscus (Hibiscus sabdariffa) calyx in order to prepare them for market. CREDIT: Rodolfo Juliani.

The team's *Community-Based Science and Market-Driven* approach completely overhauls outdated relief strategies to effectively release communities from the cycle of dependence, poverty, hunger, and malnutrition, by focusing on developing new culturally and locally-based agri-businesses, or strengthening existing ones. While previous approaches often focused on a single area or commodity, the team's holistic strategy begins with local knowledge and capacity building, incorporating market research, supply-chain development, scientific evidence, sustainable improvements to cultivation, and value-adding activities.

The projects begin from the bottom-up, by first generating local demand and fostering partnerships, providing farmers with the opportunity to learn new skills and then scaling up production at a manageable pace. Entrepreneurship training then provides farmers with skills to manage their horticultural enterprises. These transferable skills empower local individuals to form new businesses and agricultural opportunities, while training new members of their community beyond the scope of the project.

Throughout the process, Professor Simon and his colleagues support farmers with value-added technologies, such as tools to increase processing efficiency. Supported by thorough market research and the technical support of the team, farmers can then organically expand their businesses to reach regional, national, and international markets. This market-driven strategy ensures that all of the communities involved can successfully develop thriving horticultural enterprises. Demonstrating the culinary potential of African indigenous vegetables proved to be a successful strategy to engage consumers. This was done to eliminate the prior stigma associated with local plants that, while known to be nutritious, had been termed 'famine foods'. 'This perception is a barrier for farmers attempting to sell their crops in formal market places such as grocery stores, restaurants, and hotels,' says Emily Merchant, Program Coordinator, and a PhD candidate. 'One aspect of our project is working with communities to promote the historical legacy of the vegetables to increase demand across communities.'

Seeing – and tasting – the results convinced many uncertain consumers. Cultivating indigenous produce keeps the focus on the local community and culture, and helps to increase the pride and motivation of project participants. Additionally, indigenous plants work with the regional landscape and environment, ensuring future climate resilience.

The safety and nutritional analyses of indigenous crops have helped to drive international demand for some of these food plants. For example, the anti-diabetic properties of 'kinkéliba', the Senegalese bush tea, first discovered and reported by Professor Simon and his colleague, Dr Qing-Li Wu, gathered international interest, stimulating a market for kinkéliba, which is now used in foods and cosmetics. Rutgers University's progressive policy also ensures that any technologies licensed, such as for medicinal use, must provide fair benefits back to the source country.

This multi-faceted approach tackles the unique barriers to horticultural enterprise faced by communities in developing countries. For example, in many regions targeted by the projects, high-quality seed systems were not in place for horticultural crops. Previous efforts to implement horticultural systems have been limited by a lack of investment in capital and materials. Unable to access agricultural credit, communities could not afford the high transaction costs and high risks involved with setting up horticultural systems. By setting up reliable, high-quality seed systems, the project team established sustainable supplies. Additionally, micro-grants awarded to farmers and communities as part of the projects incentivised innovation, entrepreneurship, and independence.

The team has applied their model to multiple communities – using regionally appropriate horticultural crops – across sub-Saharan Africa, including Zambia, Kenya, Tanzania, Senegal, Rwanda, Ghana, and Liberia. The success of these projects across multiple communities and crops demonstrates the adaptability and transferability of the model.

Case Study: Senegalese Hibiscus (Bissap)

Communities in rural Senegal, and particularly women, face many challenges that prevent sustainable rural development.

Women participating in a community cooking day featuring African Indigenous Vegetables. CREDIT: Nthano photography.

Women in these villages tend to grow peanuts and other low-value crops that generate insufficient income to support their families. Without access to accurate market information, they are more likely to undervalue their product. Senegalese women are often marginalised in rural affairs and have poor access to land and resources.

Professor Simon and the team from Rutgers University collaborated with their core African partner, Agribusiness in Sustainable Natural African Plant Products (ASNAPP) in Senegal and Ghana, to form horticultural cooperatives in rural villages, reaching over 35 grower groups. 'By valorising their enormous contributions, this model ultimately sought to empower women by helping them access and manage their resources and making them true stakeholders in the development of their communities,' says Dan Acquaye, Founder of ASNAPP-Ghana. 'These farmers have responded by taking full advantage of the package of services to improve the quality of their production, harvest, and post-harvest treatment of hibiscus.'

Hibiscus is cultivated for the edible, fruit-like 'calyces' that form after blooming. With multiple uses including tea, cold drinks, and beauty products, hibiscus is a promising plant for horticultural development. However, before the intervention, it was largely neglected with low yields that only secured around $1 USD per kilogram.

ASNAPP together with Professor Simon's team facilitated and mentored farmer-owned horticultural start-ups by introducing good agricultural practices, improved seeds, and seeding technology that reduced planting time from 14 days to two days per hectare, saving farmers $90 USD per hectare. Through this program, the team trained over 4000 women in hibiscus cultivation and entrepreneurship, including local champions that acted as the link between the cooperatives and buyers.

By identifying the labour-intensive tasks and implementing timesaving tools, the team was able to dramatically improve the volume of produce that the groups could process. One example is the labour and time involved in processing hibiscus calyces individually prior to drying. To ensure production could be scaled up, a simple device identified in Southeast Asia was introduced to process multiple calyces at once. This ensured the groups were able to keep up as yields improved through better agricultural practices.

'In addition, implementing a robust quality assurance and control systems increases the value of the Senegalese hibiscus,' says team member Dr Rodolfo Juliani. 'The demand increased for this product due to its superior quality, leading to more marketing opportunities and higher prices for the Senegalese women growers. These systems also allow traceability from farm to table.'

Along with other value-added efforts, such as organic certification for 350 hectares of farmland, these techniques have facilitated expansion to national and international markets. The price obtained for hibiscus has more than doubled after the team's intervention strategies. Farmers sometimes argued that they could not add value to their produce; however, generating high-quality raw botanical ingredients is a cost-effective way of adding value. These quality assurance systems were transferred to local researchers, so that they were able to conduct simple quality testing in locally built laboratories.

The secure income generated from their horticultural enterprises has allowed these Senegalese groups the freedom to contribute to the development of their communities. 'The women have demonstrated their commitment to local development focused on the health and education of their children, food security, environmental sustainability, and community vitality,' says Professor Simon. Today, hibiscus is now a national crop of Senegal with significant market potential.

Transferability is Key

The team's community and science-based market-first model for horticultural development, known as Food-systems for Empowerment, Economic Development and Sustainability (FEEDS), has produced transformative changes across multiple regions and communities.

Applied throughout the sub-Saharan Africa cities of Lusaka and Chipata in Zambia and Eldoret in Kenya, FEEDS was found to be highly adaptable and demonstrated success in fostering alliances along the food system value-chain, promoting science-driven impact and policy change, adding value to community and government initiatives and building capacity for farmers and distributors, in addition to empowering the community voice. Ultimately, the FEEDS projects provided long-lasting climate-smart infrastructure change and led to millions of dollars of income generation by local growers, distributors and suppliers who are now independently operating.

INDICATORS	TARGET	ACHIEVED
Number of farmers trained in business skills	1,550	2,419
Number of individuals trained in gender awareness	650	1,228
% of registered farmers who were women	50%	40%
% of lead farmers who were women	50%	37%
Number of women trained in entrepreneurial skills	1,025	1,140
Number of farmers trained in post-harvest handling/ cold chain	1,550	2,179
Number of CASH farmers applying post-harvest technologies on their farms	80%	89%
Percent of demonstration farms with raised shade storage systems	100%	82%
Number of farmers trained in conservation agriculture	2,500	2,784
% of CASH farmers applying conservation agriculture technologies on their farms	75%	79%
Number of farmers trained in water management/water harvesting technologies	1,250	1,629
% of CASH farmers applying water management technologies on their farms	75%	75%
Number of farmers provided with early maturing/drought tolerant vegetable varieties	1,200	2,970
Sales of fresh market vegetables*	$15,000,000	$15,752,941 (USD)

*Included green beans, cabbage, leafy greens, onions, potatoes, tomatoes, and other

Table 1: An example of the economic impact of one of the team's projects relative to commercialisation of fresh market vegetables in Zambia, with farmers who had not been involved in commercial horticulture, conducted under the CASH project in Years 3 and 4 (in which production and sales began)

Kenya	Metric tons of AIVs	Annual sales data ($US)
Y4	445.86	$292,009
Y5	641.73	$527,838
% Increase	43.9	80.7
Zambia	**Number of Grocery Outlets**	**Annual sales data ($US)**
Y4	8	$336,000
Y5	11	$382,514
% Increase	37.5	13.8
As reported by some of our grower groups and female growers associations	Total AIV sales received by smallholder growers in the targeted project areas in Kenya and Zambia at project end (Y5):	$1,538,388

Table 2: Sales of African Indigenous Vegetables in Kenya and Zambia under the AIV project in the Horticulture Innovation Lab between October 2017 and October 2018, and between October 2018 and October 2019 (Years 4 and 5 of the project, in which production and sales began)

One significant FEEDS project, the USAID-funded Commercial Agriculture and Sustainable Horticulture (CASH) in Lusaka, Zambia, included partnerships with 71 farmer groups and was designed to improve their production, expand their growing seasons, and collectively market their produce. The project reached nearly 2500 farmers, around 40% of them women, providing agricultural and entrepreneurship training.

Ultimately, in the last three years of a four-year project, the groups generated over $11 million USD in sales of fresh produce. This success was due to the motivation and dedication of growers and communities selected, the intensive training provided, the focus on quality control, the use of a science-driven and market-first approach and preparation of crops for the market. The farmers had become disciplined and efficient in scheduling, selecting varieties, grading, sorting and packaging to meet buyers' needs and market requirements, including food safety.

In another project, the team introduced African indigenous vegetables to over 1,000 farmers that had never grown these crops before. After two years, sales of these crops exceeded $500,000 USD annually. One component of that study, funded by the Horticulture Innovation Lab with USAID-funds, showed that farmers growing African indigenous vegetables consumed

more of these crops themselves. That study also showed that people growing indigenous vegetables using sack gardens or other technologies in urban areas were more excited about consuming these crops when products were available, accessible and affordable.

The team's projects have reached some of Africa's most vulnerable individuals and communities. A FEEDS project in Rwanda focused on re-establishing the essential oil industry, in collaboration with World Relief, a local community-interest business called Ikirezi Natural Products, and two women's associations. The project reached over 500 people, including widows, young women and orphans impacted by the Rwandan genocide. The outcome was organically certified essential oil of geranium sold on the international market, with profits returned to communities for empowerment and reinvestment.

Key elements that allow this model to be scaled or transferable include: strengthening and empowering local champions; community engagement; building trust and confidence; ensuring real markets for crops and botanicals are available; meeting community, government and funder expectations; and providing practical solutions with human capacity building, skills training, and the introduction of new technologies and processes.

The team is now applying their successful development model to communities outside sub-Saharan Africa. 'Our new programs are designed with Rutgers University's Institute for Food, Nutrition and Health's Center for Agricultural Food Ecosystems to transfer and apply the "Community-Based Science, Market-First Sustainable Horticulture for Urban Food Security" model to the diverse and economically challenged and food insecure communities in the US struggling in a COVID-19 environment,' says Professor Simon.

Women selling African Indigenous Vegetables at the market.

'We all continue to change and learn from each other and our community partners. After all these years of being engaged in international development, seeing successes and realising that some of our initial efforts fell short, we came to recognise how fortunate and blessed we are to have worked with so many people in so many countries and stayed focused on empowering the lives of others using horticulture and natural products in the broadest sense – herbs, spices, botanicals, indigenous fruits and vegetables,' he adds.

'As it's working, we now have a responsibility to build upon knowledge gained and lessons learned to help others build community-based resilience against poverty and malnutrition. Our global ideas for addressing food systems and food insecurity have been built over time from our original market-first science-driven model to the demonstrated work and success of our resilient, food systems for empowerment, economic development and sustainability model in sub-Saharan Africa.'

Ingredients for Success

Professor Simon believes that the team's success has been largely due to the members' creativity and diversity, their commitment to facilitate change for the benefit of the communities, their recognition that real economic improvement that changes the lives of individuals and communities creates motivation and incentive, and the local champions in the community that bring it together and make it happen.

Having a real commercial economic focus, coupled with an emphasis on developing strong technical skills in building, repairing and farming, allowed the projects to achieve significant economic improvements, while adhering to a community-led approach that prioritised economic, environmental and cultural sustainability.

'These initiatives have tested the merging of science, theory and practical solutions, while respecting national and local governments and the embedded cultural norms of tribal and ethnic groups in which we have been honoured to be invited to work,' says Professor Simon. 'The 20+ year long-term partnership with ASNAPP-Ghana in particular has really helped transform the models developed.'

'The strong public and private sector partnerships, and the trust that was developed among diverse stakeholders paved the way for overcoming many of the stumbling blocks that face international development projects,' he adds. 'Developing a shared vision in providing solutions to local hunger, lack of employment opportunities and viewing each of our stakeholders and partners with respect allowed us to use horticulture and indigenous plants as the economic driver in particular for women and youth.'

As a global community, we need to change. The global issue of poverty, malnutrition, and hunger requires proven solutions. The increasing pressures from climate change and environmental degradation demand these solutions are sustainable.

The continued and repeated successes of Professor Simon and his team's agri-business model demonstrates that transformative, sustainable change is possible, and that the strategic inclusion of horticultural crops and indigenous foods and botanicals can provide economic, cultural and environmental sustainability and make a difference in increasing food security by improving the health, nutrition and income opportunities of so many. This model method has the power to fuel an agricultural revolution for a better future for all, and it's ready to be replicated and scaled.

Meet the Research Authors

 James E. Simon
 Dan Acquaye
 Ramu Govindasamy
 Julie Asante-Dartey
 Rodolfo Juliani
 Babou Diouf
 Malainy Diatta
 Petrus Langenhoven
 Emil Van Wyk
 Nicholas Hitimana
 Dena Seidel
 Emily Merchant
 Larry Amakuze
 Steve Weller
 Daniel Hoffman
 Qing-Li Wu

CONTACT

W: http://newuseag.rutgers.edu
W: https://rucafe.rutgers.edu/
W: https://www.asnapp.org.gh/
W: https://www.ikirezi.com/
E: jimsimon@rutgers.edu

FUNDING

MCA-Namibia
US Foreign Agricultural Service
United States Department of Agriculture (USDA)
USDA – National Institute of Food and Agriculture
The New Jersey Agricultural Experiment Station
United States Agency for International Development (USAID)

ACKNOWLEDGEMENTS

The team wishes to thank the USDA and the US Agency for International Development (USAID) for their funding and support since 2000 under the many-awarded projects from ATRIP to ASNAPP to Partnerships in Food Industry Development for Natural Products and African Indigenous Vegetables (AIVs). The most recent includes the research supported partially by the Horticulture Innovation Lab with funding from USAID (EPA-A-00-09-00004), as part of the US Government's global hunger and food security initiative, Feed the Future, for 'Improving nutrition with AIVs' in eastern Africa and prior USAID initiative including Partnership in Food Industry Development for Natural Products. The team also thanks the US State Department, Oxfam International, the New Jersey Agriculture Experiment Station (HATCH projects 12131 and NJ12158), the Rutgers Institute for Food, Health and Nutrition, The Rutgers Center for Food Agricultural Ecosystems (RUCAFE), Academic Model Providing Access to Health Care (AMPATH), Mirror of Hope CBO, IKirezi, the World Vegetable Center (WorldVeg), Kenyan Agricultural and Livestock Organization (KALRO) and Agribusiness in Sustainable Natural African Plant Products (ASNAPP), World Relief, The Association de Sante, University of Cheikh Anta Diop, Dakar, Stellenbosch University and the University of California- Davis. They give special recognition to the following individuals for their support and encouragement: Jerry Brown, Carol Wilson, John Bowman, Beth Mitcham, Kelly Bauer Bennett, Elton Jefthas, Leopold Van Huyssteen, Soji Adelaja, Magette Wade, Bill Hallman, Brian Schilling, Xenia K. Morin, Mark Robson, Fekadu Dinssa, Norah Maiyo, Naman Nyabinda, Mebelo Mataa, John Shindano, Himoonga Bernard Moonga, Christine Ndinya, Martins Odendo, Elke Couch, Sandy Turketti, Craig Fulton, Andries Arendse, Lupiya Sakala, Evaristo Nyeleti, Nickson Mwale, Inonge Siziya, Geoffrey Silungwe, Samuel Mainga, Christabel Kabole, David R. Byrnes, William Reichert, Mwangala Mbeweu, Bo Yuan, Kenneth Chali, Larry Hwang, Justus R. Ochieng, Victor Afari-Sefa, Albert Ayeni, Emmanuel Bassene, Charles Quansah, Richard Akromah, M.L.K. Mensah, Rob McCaleb, Mark Blumenthal, and Thomas Nyawir.

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ETHNIC FOODS IN THE RECIPE FOR FARMING SUCCESS

Farmers in the East Coast of the US are struggling to compete against the larger farms of other regions. Coupled with rising production costs and increasingly difficult growing conditions, producing conventional commodity crops is no longer viable for these farms. Switching to speciality and niche ethnic crops could help these farmers break into a growing market, improve profitability and future viability – and help fulfil the needs of ethnic communities. **Dr Ramu Govindasamy** from Rutgers University uses a market-first approach to investigate and develop opportunities for farmers to transition to ethnic crop production.

Mutual Benefits of Farming Ethnic Crops

Imagine the taste of home. The cuisine that comes to mind may bring with it a wave of nostalgia. The taste and smells of our favourite foods have the power to bring memories forth from the recesses of our minds. Food can comfort. It can bring joy. It can bring families and friends together and remind us who we are.

It is little wonder then, that food has a central role in so many cultures and communities, and why families that have emigrated to other parts of the world often wish to retain the foods from their homelands. It can help people hold onto a sense of heritage and identity in a scary, new world.

'Ethnic' foods, fruits, vegetables, and herbs – those pertaining to a specific group with shared attributes, such as culture or country of origin – often have unique characteristics not shared with any of the conventional crops grown in the US. They are imported to fulfil the demands of ethnic communities or are grown on a limited scale. Many ethnic consumers are willing to pay a premium for these foods, when they can obtain them. As such, opportunities exist for local farmers to fill this niche market by moving away from production of traditional commodity crops and towards production of ethnic crops.

These opportunities are becoming increasingly important for farmers along the East Coast of the US. East Coast farms have been at risk since the 1980s because of highly volatile market prices. Additionally, East Coast farmers operate on relatively small land areas in comparison to the larger crop farmers from the mid-West, resulting in a higher production cost per unit of crop output. This puts them at a competitive disadvantage and threatens the long-term viability of their operation. For traditional 'commodity crop' farms (growing staples such as corn and soybean) large acreage and lower relative production costs are critical to be economically feasible.

Many East Coast farmers have already begun transitioning to the production of speciality and niche crops, including ethnic crops, to increase profitability.

By tapping into a different market, these farmers mitigate the competitive disadvantage they have when producing similar crops to their larger competitors. The rapid expansion of ethnic populations along the East Coast – and their purchasing power – presents local farmers with significant opportunities to forge a niche for themselves within a market that is likely to continue expanding in the future. Additionally, being within proximity of densely populated areas in the region

may help to reduce the costs and difficulties associated with distribution and ensuring produce is still fresh when reaching the shelves.

But trying to capitalise on any market without first understanding that market is to tempt disaster. East Coast farmers need strategies underpinned by reliable evidence before beginning the transition to ethnic crops. Understanding the market and the needs of potential consumers is vital to ensure long-term economic viability. Equally important is identifying ethnic crops suited to the growing conditions in the US, using reliable scientific evidence.

Dr Ramu Govindasamy of Rutgers University and his collaborators have been developing strategies for East Coast farmers to transition to ethnic crop production based on scientific and market evidence. He emphasises a market-first approach that helps to mitigate grower risk and guarantee success by matching the needs of consumers more precisely with food production. By developing coordinated production and cooperative marketing strategies between farms along the East Coast, Dr Govindasamy aims to prevent rapid over-production of specific crops and the associated price depression, and ensure year-round availability of these foods for ethnic communities throughout the region.

Understanding Ethnic Consumers

Ethnic populations contribute a great proportion of the total US population growth. Between 2000 and 2010, the US population increased by 9.5%. In contrast, the Hispanic population increased by 34% and the Asian population increased by 33% during the same period. Over one million foreign-born people become legal permanent residents of the US each year. The East Coast region, in particular, is characterised by the high proportion of the growing ethnic population.

By extrapolating results obtained through consumer surveys to population sizes, Dr Govindasamy estimated the potential ethnic produce markets for different ethnic subgroups along the East Coast. He estimated the annual market for Chinese produce at US $245 million to $296 million, while appealing to Asian Indian communities could capture a market worth US $190 million to $230 million per annum. Similar potential exists within the Hispanic community market, with the East Coast Mexican market annual worth estimated at US $281 million to $362 million, and the Puerto Rican markets potentially netting US $531 million to $655 million per year.

Although Dr Govindasamy's consumer profile investigations revealed some similarities between ethnicities and ethnic subgroups useful for creating a general profile for the consumer group as a whole, exploring the relevant characteristics, shopping patterns, preferences, and opinions of ethnic subgroups is critical for effectively targeting specific ethnic markets. 'The type of food cooked, patterns of purchasing produce, and amount spent on food are very centric to and dependent on cultural trends,' says Dr Govindasamy.

For example, the Hispanic community is diverse – in addition to Mexicans and Puerto Ricans, Hispanic communities also originate from Cuba, Central and South America, and other Spanish-speaking cultures. Dr Govindasamy found that some of the most promising ethnic crops to cultivate and market to appeal to the East Coast Mexican community include tomatillo, jalapeno chili peppers, calabacita squash, and pablano or ancho chili peppers. In contrast, promising crops favoured by Puerto Rican communities include culantro, pepinillo, batata sweet potatoes, and aji dulce sweet peppers.

Understanding where and how different ethnic communities prefer to shop for their produce can also inform effective distribution and marketing strategies. 'Many ethnic communities have their own channels of produce distribution outside the traditional retail supermarket industry and few studies have studied this informal and growing industry and its consumer base,' explains Dr Govindasamy. In recent research investigating the ethnic food preferences of Chinese, Asian Indian, Mexican, and Puerto Rican consumers, he found that 88% of the individuals surveyed bought their ethnic greens and herbs from ethnic grocery stores. By expanding and developing distribution networks based on these results, farming businesses could capture more of the potential consumers.

Putting these strategies in place could also help East Coast farmers future-proof their enterprises by priming them for emerging markets. 'As ethnic demographic profiles change, fresh produce marketers and commercial growers aware of such trends may be able to alter or add to their selection of crops to effectively respond to new trends and changes in demand,' Dr Govindasamy explains.

Refining Production Strategies

In addition to informing strategies for marketing and distribution, Dr Govindasamy also helps farmers identify suitable ethnic crops for production in the East Coast through careful selection and subsequent field trials. In his research on Asian Indian and Chinese consumers, Dr Govindasamy used surveys to identify the vegetables, leafy greens, and herbs most sought by these communities. Over 100 potential Asian ethnic crops were identified, narrowed down by a panel of experts based on production barriers, such as climate, growth cycle, seed availability and regulation, and market competition. In another study, which also included Mexican and Puerto Rican consumers, Dr Govindasamy and his panel of experts narrowed down the list of potential ethnic crops to 10 per ethnicity before using surveys to rank them in terms of popularity.

Field production trials were used to refine growing strategies to maximise productivity. Assessing plant vigour, yield, and growth rate over multiple years and across different regions of the East Coast helps farmers select the most appropriate ethnic crops to produce for their individual farms. As these plants are not native to the US, careful consideration was also given to the potential for these species to become invasive. Appropriate management strategies were devised from this evidence, such as timely harvesting to prevent plants setting seed. The findings from these trials help farmers make informed decisions about which ethnic crops, and which cultivars, are economically viable for commercial production.

In addition to production trials, Dr Govindasamy and his team conducted nutritional assessments on the ethnic crops selected. This revealed that many of these food plants are nutrient dense and a rich source of vitamins and minerals. Scientific analyses such as these can drive market interest, and may even help ethnic foods reach the mainstream markets. 'In addition to taste and visual appearance, today's healthy choice for food calls for increased nutritional value from eating a diversity of horticultural crops,' explains Dr Govindasamy, 'Mainstream consumers may find expanded or even better choices from ethnic vegetable, leafy green, and herb cultivars.'

Dr Govindasamy and his team's market-first, science driven approach has proven successful for agricultural business enterprises around the world. By providing East Coast farmers with reliable, thorough strategies for transitioning to ethnic crop production, their future economic viability is vastly improved. By investigating ethnic consumers' preferences and needs, these communities get improved access to their favourite foods from their homelands. Using Dr Govindasamy's approach, everyone's a winner.

Meet the researcher

Dr Ramu Govindasamy
Department of Agricultural, Food and Resource Economics
Rutgers University
New Brunswick, NJ
USA

Dr Ramu Govindasamy is Professor of Agribusiness Marketing at Rutgers University. Here, he also serves as Chair of the Department of Agricultural, Food and Resource Economics. Dr Govindasamy's nationally and internationally recognised research has led to over 100 publications in peer-reviewed journals, 150 professional and invited presentations, and 45 external research grants. In the USA, his research focuses on direct marketing, organic produce marketing, ethnic produce marketing, and natural products including herbal medicine. Within a few years of his appointment at Rutgers University, Dr Govindasamy was awarded the Research Excellence Award. He was also awarded the Presidential Emerging Leadership Award by the Food Distribution Society in 2004, and has served as the president of the association in 2018.

CONTACT

E: govind@sebs.rutgers.edu
W: https://njaes.rutgers.edu/personnel/individual/112

KEY COLLABORATORS

Dr Albert Ayeni, Department of Plant Biology and Pathology, Rutgers University
Dr Kathleen M. Kelley, Department of Horticulture, The Pennsylvania State University
Mr Stephen J. Komar, Mr Peter Nitzsche, Dr William J. Sciarappa, Mr Richard W. Van Vranken, Agricultural & Resource Management Agents, Rutgers University
Dr Frank Mangan, Department of Plant, Soil and Insect Sciences, University of Massachusetts Amherst
Dr Gene McAvoy, Institute of Food and Agricultural Sciences Hendry County Extension, University of Florida
Dr Brian Schilling, Rutgers Cooperative Extension, Rutgers University
Dr James E. Simon, Center for Agricultural Food Ecosystems, and Department of Plant Biology, Rutgers University
Dr Shouan Zhang, Department of Plant Pathology, University of Florida

FUNDING

Cooperative State Research, Education and Extension Service – United States Department of Agriculture (USDA)
National Institute of Food and Agriculture (NIFA) – USDA

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RUTGERS
THE STATE UNIVERSITY OF NEW JERSEY

COOPERATIVE STRUCTURES: FINDING A WAY FORWARD FOR MID-SIZE FARMS

More than 80% of agricultural land in the US is managed by farmers whose operations fall between small-scale farms with direct access to local markets, and larger industrialised farms. These farmers in the 'middle' increasingly struggle to find a place within the larger food production system. Through his work as part of the 'Agriculture of the Middle' Initiative, **Dr Thomas Gray** of the Rural Business-Cooperative Service at the US Department of Agriculture has been studying different types of cooperative structures for best adaptability to socio-economic and food consumption patterns for mid-size farm survival.

Dilemmas of Survival

Over the last several decades, two parallel agriculture and food systems have emerged from within the larger US agricultural system. These two systems sit at opposite ends of a size continuum and are characterised by very different production types. At the 'small farm' end, production is predominantly organic, environmentally sensitive and local, and is sold at farmers' markets, farm stands and community-supported agriculture markets. Production is diverse and niche, and is often within metropolitan commuting patterns, with annual sales typically peaking at $2500.

Farms at the larger end of the continuum account for huge volumes of commodities marketed at regional, national and global levels through corporate food chains. Unlike the diversified products of the smallest farms, commodity production involves homogeneous, undifferentiated products, with financial gains based on volume rather than niche specialisation. These large farms typically account for annual sales of over $1 million.

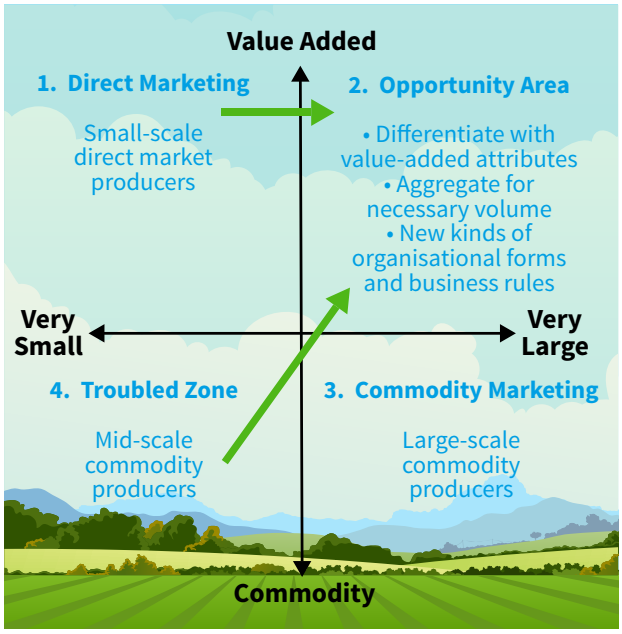
In an era when total US farm numbers have decreased dramatically, the numbers of both the smallest and largest farms have increased. Between the two extremes are 'agriculture of the middle' (AOTM) farms, sometimes referred to as the 'disappearing middle'. 'These farms struggle financially due in part to their specialisation in large volumes of low-value homogenous products, which places them in direct competition with larger, industrialised farms,' explains Dr Thomas Gray of the Rural Business-Cooperative Service, US Department of Agriculture (USDA). 'Low returns per unit of product combined with high costs of inputs places large numbers of mid-size farms in a cost-price squeeze. This squeeze is often followed by bankruptcy or acquisition by a neighbouring farm.'

Drs Gray's recent research investigates the AOTM, and possible cooperative solutions for revitalising mid-size, family-run farms.

Family Farming and Historical Changes

Mid-sized farms tend to be family run. However, the end of the first world war marked the beginning of a progressive industrialisation of production with mechanical advances followed later by chemical, biological and information technology innovations. These developments, along with market competition, pressured family farms to expand production to larger and larger acreages with more intensive production per acre. As scale increased, the more traditional organisation of farming around family ownership, family management and family labour began to come apart. Many family farms ultimately ended up being part of multi-million-dollar operations requiring year-round hired labour and some with hired management.

US Census of Agriculture numbers from 2017 are illustrative of these tendencies: 67% of total agricultural production was accounted for by just 4% of total US farms. These farms were among the largest, all having over one million dollars in sales. However, over 80% of farmland in the US is still managed by farmers whose operations fall between small-scale and large industrialised farms.



Socio-economic and Ecological Trade-offs

The continued thinning-out of family farm structures has not occurred without auxiliary losses involving various other socio-economic and ecological factors. Family incomes, education levels, number of local businesses, and involvement in local organisations all tend to be greater in communities surrounded with a base of small to mid-size farms than in communities in industrialised farm contexts.

Farmers, wholesalers, retailers, universities, governments, NGOs, and community development specialists have sought to protect smaller and AOTM farming, given its several secondary and tertiary socio-economic and ecological benefits.

Agriculture of the Middle Options

Dr Gray's collaborators, Dr Steve Stevenson and Dr Fred Kirschenmann, have constructed an options grid that illustrates the different choices for US farms (**see figure**). AOTM farms are depicted in the lower left quadrant and labelled a 'troubled zone'.

A survival path exists for some producers to acquire and consolidate neighbouring farms, in a process of producing larger volumes of commodities (quadrant 3). This is not a path many mid-scale farmers identify as financially feasible nor personally desirable, and comes with the continued loss of family-structured farming. A few AOTM farms may be able to engage in direct marketing (quadrant 1), and make the necessary shift to organic and relationship marketing. However, this is not feasible for most AOTM farmers, because they are too distant from these markets and have too much volume.

Quadrant 2 may hold the most opportunity for AOTM farms, based on consumer desires for 'values-dense' food products that emphasise socio-economic and ecological sustainability.

'However, making the shift to values-dense, differentiated products would require changes in production. Probable success could be enhanced with brand development, advertising, processing and product moulding, and value-chain development. Most farmers would be unable to afford these functions,' says Dr Gray. 'However, all could be performed within the context of an agricultural cooperative.'

Cooperatives: A Possible Solution

Cooperatives are formal social movements, often established in reaction to various social-economic injustices, or market failures. Cooperatives may be the best choice for AOTM development, given they are structured not only as businesses, but also as democracies, and as such, have built-in mechanisms for resolving conflicts of interest among various stakeholders.

As part of the Agriculture of the Middle: Research, Education and Policy group, Dr Gray has been examining cooperative membership structures to determine which form may be most appropriate to help vitalise the mid-size farming category. This work is centred within a project at the USDA's National Institute of Food and Agriculture and various US Universities (agofthemiddle.org).

'Our central goal is to create a niche for AOTM farms that could improve their survivability along larger socio-economic and environmental values,' Dr Gray explains. He cautions, however, that this task is challenging as it involves building business sustainability against massive industrialisation, corporate conglomeration, and evolving technologies.

Local, Centralised or Federated?

Historically, agricultural cooperatives have utilised three predominant organisational structures: local, centralised and federated (though there are other forms). As part of the AOTM Initiative, Dr Gray has assessed each of these, in the context of socio-economic changes in production, cooperative organisational form and consumption, to determine which structure is best positioned to support the survival of mid-size farms.

Local cooperatives are the most bottom-up of the three structures. They may have as few as 10–15 members or as many as 500–1000. Services predominantly involve the joint purchasing of supplies and collective readying and marketing of farm output. Formal democratic control runs from the members as a group to the local organisation, with members electing a board of directors that sets longer run policy for the organisation. Most members live in close proximity to each other and often know each other personally, lending the cooperative a degree of informality unusual in larger organisations.

As open, transparent and democratic organisations, local cooperatives can serve as a vehicle for assembling farmer voices and achieving joint actions – providing farmers with market power and access well beyond what most small to mid-scale farmers could ever achieve as individuals. As independent businesses, with local bases, they represent a dispersed, decentralised approach that can empower farmers to take collective actions to follow sustainability programs. Responsiveness to local agendas almost always occurs by definition in locals, while creativity, commitment and shared identities can evolve out of these actions.

However, as an overall policy approach to national agendas, Dr Gray comments that local co-ops as the sole strategy for mid-size farm survival would likely lack coordination across multiple individual facilities, and nationally. Therefore, they could not easily provide sufficient scale to offset competition from large, well-coordinated, regional and multinational investment-oriented firms.

Similar to local cooperatives, members of a centralised co-op belong to a single organisation. Unlike local co-ops however, memberships often number in the thousands and are typically spread over large geographic regions. Local facilities exist, which provide various services conquerable to those offered in any local cooperative; but dissimilarly, the locals are business branches only, and are not cooperatives themselves. Members elect a board, which is typically mandated to provide strategic planning and board direction for the cooperative.

Centralised co-ops have various advantages of scale, scope and resources that locals do not have. Scale and centralisation allow them to achieve uniformity of products and services regionally, by operating all local units from the centre. Such co-ops have lower operating costs due to centralised control of the handling and marketing of products, greater bargaining power in the marketplace, and a strong ability to adapt to rapidly changing economic conditions.

However, decision making, and operational control are concentrated in the co-op's headquarters. This means that rather than being characterised by direct participative democracies, like in local co-ops, centralised cooperatives tend to take shape as democratic bureaucracies. This mutes opportunities to develop mutual identities, and members may lose interest in participating in the organisation. An internal logic parallel to return on investment criteria can take precedence, and cooperative operations and member involvement may begin to look similar to investor-oriented firms. Under such situations, achieving the sustainability goals of AOTM farmers becomes more difficult and consumer trust may be lost.

Federations as Both Centralised and Decentralised

Dr Gray's work leads him to conclude that a combination of local and centralised cooperative models could be the most appropriate solution for pursuing the interests of the middle. This combination is represented by the federated cooperative model, where a collective group is formed from local cooperatives.

In a federation, farmers hold membership in local cooperatives, which in turn, form a cooperative of locals. Locals own the federation and typically provide large proportions of its capital needs. They also elect a board of directors, and this board hires the federation management and provides strategic planning and long-range direction to the larger cooperative.

Like centralised cooperatives, federations are organisationally complex, but this bureaucratic complexity tends to be offset by a direct participative democracy at the local level. Because the federation is built from the bottom-up, local members' interests may be better expressed, and member contact more readily maintained. Therefore, federations can appropriate various benefits from size and scale, resources for product development and branding, coordination advantages from member-centralisation, and space to compete for a competitive market presence. Member engagement at the local level can produce a sense of community, as well as a reinforced and shared identity.

Considering socio-economic context, history and tensions, federated cooperatives seem a likely choice to accommodate the several agendas of family-close, community embedded, environmentally sensitive mid-size farms. They represent a possible path forward to offset the bleeding out of their current commodity specialisation between the environmentally sensitive direct marketing farms and large commodity producers.

Like all cooperative types, Dr Gray cautions that federations must be chosen and monitored with caution, given their inherent capacity for internal tensions that are intrinsic to any cooperative structure. However, planning for and managing such tensions with the prudent use of member governance structures should help keep the federation aligned with local needs, and the larger consumption demands for socio-economic and ecological products attuned to sustainability concerns. Such strategies could open up greater possibilities for farmers and their cooperatives with positive and widespread benefits for the wider communities of which they are an essential part.

Meet the researcher

Dr Thomas Gray
Rural Development
United States Department of Agriculture
Washington, DC
USA

Dr Thomas Gray studied for both his master's degree in Agricultural Economics and his PhD in Rural Sociology at Ohio State University. He also holds a master's degree in Social Work from the Catholic University of America and has completed psychoanalytic training at the Institute of Contemporary Psychoanalysis in Washington DC. Dr Gray is employed by the USDA, Rural Development, and is affiliated as a 'Cooperative Scholar' with the Canadian Centre for the Study of Cooperatives. Dr Gray's research focuses on cooperatives at three levels of analyses – micro and member participation studies, meso and organisational analyses of governance, and macro on contextual issues such as changes in the structure of agriculture. Most recently, in 2019, he received a travel grant to study governance in Japanese agricultural cooperatives.

CONTACT

E: thomas.gray@usda.gov
W: https://www.rd.usda.gov/programs-services/all-programs/cooperative-programs

KEY COLLABORATORS

Lauren Gwinn, Oregon State University
Kathryn De Master, University of California-Berkely
Fred Buttel, University of Wisconsin
Thomas Lyson, Cornell University
Steve Stevenson, University of Wisconsin
Fred Kirschenmann, Iowa State University

People affiliated with the Agriculture of the Middle Task Force
People affiliated with the Multistate project, NC-1198, 'Renewing an Agriculture of the Middle', USDA, National Institute of Food and Agriculture

FUNDING

USDA, Rural Development
USDA, National Institute of Food and Agriculture

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USDA United States Department of Agriculture
Rural Development

CREATING NUTRITIOUS BABY FOOD FROM LOCAL AND AFFORDABLE PRODUCE

Malnutrition, occurring as either a lack of food or not eating enough of the right types of food, is a significant concern in many African countries, particularly for children. To address this issue, **Dr Marlyse Leng** and her colleagues at the University of Douala in Cameroon have recently developed a nutritious weaning food for infants, made from an endangered yam species to increase its production and use. After processing the yam with other key nutrients into an optimised formulation, they explored the food's nutrient availability and antioxidant activity in comparison to other products.

Weaning Formulations

Mothers often decide to start introducing their babies to solid foods alongside breastfeeding once they reach about 6 months of age. In Cameroon, the most commonly used supplementary weaning food for infants is based on maize flour. However, these formulations do not provide all of the essential amino acids, meaning that they can sometimes contribute to malnutrition. In addition, these cereal-based foods also contain several compounds called 'antinutrients', which interfere with the absorption of nutrients.

In contrast, yams and other tubers contain only low levels of the compounds known to affect absorption. *Dioscorea schimperiana* is a nutritious species of yam that is grown in Cameroon. To address childhood malnutrition, Dr Marlyse Leng and her colleagues at the University of Douala have been developing a weaning food for infants based on this variety of yam.

'This yam is an endangered species, and we wish to enhance its use,' adds Dr Leng. 'It is also the only yam with a traditional dying process technology.' This drying technology makes this particular variety ideal for processing into a flour for use in a weaning formulation.

A Yam-based Formulation

In addition to providing energy, the range of bioactive compounds in yam flour can also confer numerous health benefits to infants. For example, as malnutrition results in a disruption of the body's antioxidant defences and produces damaging free radicals, the antioxidants in yams may lead to overall health improvements. However, dried yam would not provide infants with all of the necessary nutrients on its own. Consequently, Dr Leng and her colleagues developed a yam-based formulation supplemented by beans, nuts, carrots and egg shell.

The flesh of *Dioscorea schimperiana* varies in colour from yellow to red.

Therefore, Dr Leng and her colleagues investigated the nutrient and antioxidant composition of yams of three different colours, to determine whether one colour is superior over the others. To begin their investigation, the research team purchased all the ingredients they needed from local markets. They bought dried yam slices, and categorised them according to the colour of their flesh: yellow, red, and yellow with red speckles.

The team processed all of the components, including seeds, nuts, carrots and egg shells, to remove any contaminants. They then prepared flours from the three differently coloured yams, and mixed these with the other milled ingredients to create several different versions of their weaning formulation.

To determine the nutrient profiles of these mixtures, Dr Leng and her colleagues ran a number of analyses to determine their levels of protein, fat, fibre and carbohydrate. In addition, they assessed the levels of vitamins, minerals and antioxidants in the preparations.

The researchers found that in the yams with red flesh, the desirable antioxidants are more prevalent than in yams of the other two colours. Conversely, they also found that for some compounds, such as iron, proteins and sugars, red yams contained lower levels compared to the yellow and speckled types.

Meeting Requirements

The team assessed their prepared formulations alongside existing weaning foods and also against three global standards, to investigate whether they fulfilled the required energy and nutrient composition. In all cases, they found that the yam preparations met the three key standards for total energy, water, ash and carbohydrate.

For protein, which is a vital component of weaning foods, the yam preparations achieved appropriate levels based on their 'Protein Efficiency', or 'PE ratio'. This ratio describes the amount of protein in a food compared to the total energy. The PE ratio of the team's formulations was approximately 13%, which aligns with the recommended range of 6–15%. The required range for fats is 20–40%, and the team found that their yam preparations provide 19–22%.

The researchers also found that their new products contained the recommended level of carbohydrate. Dr Leng explains that this is beneficial even in cases of protein malnutrition, as carbohydrate effectively spares the body's own protein and fat reserves. As some of this carbohydrate is sugar, the sweetness may make the formulation more desirable to babies, increasing the amount they consume.

Antioxidants and Minerals

Dr Leng and her colleagues then assessed the levels of two key bioactive compounds: pro-vitamin A carotenoids and the biologically active form of vitamin E, alpha-tocopherol. They found that yams with red flesh had greater levels of both carotenoids and alpha-tocopherol, compared with both the yellow and speckled types.

Overall, the 'retinol activity', which is a measure of the total amount of pro-vitamin A carotenoids, did not meet the World Health Organization requirements. Indeed, the red-fleshed yam, which exhibited the highest retinol activity, achieved less than half of the desired requirement of this vital component.

Dr Leng's student, Pascal Tobit, who participated in the study.

The researchers also discovered that levels of phenolic compounds varied depending on the colour of the yam flesh. Interestingly, they found that there was no correlation between the polyphenol content of their yam products and total antioxidant activity. While this finding appears to be at odds with our understanding, Dr Leng proposes that the high antioxidant activity found in the flour with the lowest levels of bioactive compounds may be a result of synergistic actions of other compounds, effectively enhancing the antioxidant 'power' of the yellow/red combined flesh.

The scientists then assessed the levels of two key minerals, specifically iron and zinc. They found that the speckled yams had the highest levels of iron, followed by the yellow and red types. The opposite was found for zinc: the red and yellow yams showed the highest concentrations, while the speckled yams had the lowest levels.

Nutrition Related to Infant Age

Weaning foods are expected to provide at least 0.8 Calories per gram to supplement breastfeeding. The calorific needs of children vary with age, with a 6-month-old child needing an additional 200 Calories daily to supplement breastfeeding, while a child in the 12–23-month age group requires an extra 550 Calories each day. Dr Leng and her colleagues investigated three age groupings, 6–8 months, 9–11 months and 12–23 months, and determined that children's energy needs could be met by feeding them 50 grams, 75 grams, and 137 grams of their yam-based formulations, which would provide 200, 300, and 550 Calories, respectively.

As the yam flours are highly energy dense, with a calculated energy of over 4 Calories per gram, the energy needs of the 12–23-month age group can be satisfied by providing just one meal per day of this new formulation. This is a viable option, based on the average 12–23-month-old child's ability to consume approximately 30 grams of food per kilogram of body weight. In addition, Dr Leng notes that this quantity of food will provide high levels of both protein and lipids that fulfil the child's requirements.

After investigating the levels of available vitamins and minerals in the weaning foods at the quantities required to meet energy needs, Dr Leng and her colleagues note that the levels of vitamin A and alpha-tocopherol do not meet the minimum amounts as outlined by the World Health Organization. Therefore, the team would need to supplement their formulation with additional quantities of these vitamins.

For zinc and iron, the precise amounts that a child can absorb are related to the bioavailability of each mineral. The team found that even when assuming a high bioavailability of zinc and a 15% bioavailability of iron, the levels of iron and zinc do not meet the needs of children in the 6–8-month category. Similarly, in the 9–11-month group, the formulations' zinc levels can provide 100% of the daily requirement under high bioavailability conditions, while the iron needs are not met in the same conditions.

For older children, in the 12–23-month group, 100% of the day need for zinc and iron can both be met even when bioavailability is at 10% for iron and within the medium range for zinc. This means that even when the bioavailability is not maximal, the team's weaning food still provides the necessary levels of minerals to 12–23-month-old children.

Outcome and Recommendations

Dr Leng and her colleagues show that a yam-based weaning food, prepared in combination with other milled ingredients, provides children between the ages of 12 and 23 months old with the energy, protein, fats, vitamins and minerals that they need, as long as their diet includes another source of carotenoids, such as carrots, apricots or watermelons. Furthermore, the many antioxidants present in the team's formulation are known to be greatly beneficial, and can lead to overall health improvements in children. Overall, they recommend that a daily portion of around 137 grams for children in this age group is ideal.

In future work, the team suggests that they could greatly improve the vitamin and mineral content of their formulations by optimising how the fresh yams are processed, as the most common traditional processing method leads to nutrients leaching into the water during boiling, which occurs before the drying step. They hope that their affordable, sustainable and locally produced baby food will soon be available on the market, towards combating malnutrition in Cameroon and beyond.

Meet the researcher

Dr Marlyse Solange Leng
Basic Science Department
Institute of Fisheries and Aquatic Science at Yabassi
University of Douala
Cameroon

Dr Marlyse Solange Leng received her PhD in 2012 from the University of Ngaoundéré in Cameroon. Alongside her PhD research, she worked as a lecturer in the Department of Biochemistry at the University of Douala. At this university, she has since progressed Associate Professor and Head of the Basic Science Department at the Institute of Fisheries and Aquatic Science at Yabassi. Much of Dr Leng's research focuses on strategies that improve the nutrient availability of foods in the developing world. Her team has investigated approaches to improve the nutritional benefits from local foods, enhance storage and develop food supplements that address the significant nutritional deficiencies in the region.

CONTACT

E: lengmarso@gmail.com

KEY COLLABORATORS

Pascal Tobit, Adelaide Mawamba Demasse, Inocent Gouado – University of Douala, Cameroon
Robert Ndjouenkeu – University of Ngaounderé, Cameroon
Kristine Wolf, Harshadrai M. Rawel, Florian J. Schweigert – University of Potsdam, Germany

ACKNOWLEDGEMENTS

Dr Leng would like to thank TWAS-DFG for financial support for the project. She also gratefully acknowledges the Institute of Nutritional Science of the University of Potsdam, Germany, for providing resources for the laboratory aspects of this work.

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INVESTIGATING FUNCTIONAL PROPERTIES TO PRODUCE EVEN BETTER PEANUTS

Peanuts are a nutritious and sustainable food staple in many regions across the globe, as well as being enjoyed for their rich flavour. As such, the peanut industry is continually striving to improve peanut crops and the methods used to produce our favourite peanut-based foods. **Dr Lisa Dean** and her team at USDA-ARS have been investigating the flavours, nutritional compositions and physical properties of peanuts, with the aim of helping peanut growers and food manufacturers enhance the quality of the peanuts produced in the USA.

A Sustainable Superfood

Peanuts have everything going for them. Packed with nutrients and protein, they are convenient, relatively inexpensive, delicious and sustainable. As well as being an energy-dense crop, requiring less land to produce the same amount of food than most common crops, peanuts have numerous other environmental benefits.

For instance, they require far less irrigation than tree nuts, as their roots can penetrate deep into the soil. As a nitrogen-fixing plant, peanut crops also replenish the soil with essential nitrogen, and need little or no fertiliser to grow. With the global population expected to reach nine billion by 2050, there is a real need for sustainable, nutrient-rich foods. Thus, peanuts are key to ensuring global food security into the future, and much research has been dedicated to making them even more nutritious, long-lasting, sustainable and delicious.

The Source of Peanut Flavours

In the USA alone, approximately five billion pounds of peanuts are already produced annually, with these peanuts being particularly prized for their delicious roasted flavour.

The flavour differences between peanut varieties are attributed to their unique composition of 'metabolites', which are compounds produced through normal cellular activities. Many of these metabolites are familiar to consumers because of their health benefits. For example, the healthy fats, amino acids, vitamins and minerals present in peanuts also contribute to other properties important to farmers and food manufacturers, such as disease resistance and shelf life.

The properties of peanuts are continually being improved through selective breeding. These improvements often rely on altering the metabolite profile, and thus also impact the flavour of the peanuts. Since flavour is the predominant factor affecting consumer acceptance, understanding of the relationship between metabolites

and flavour is a priority for food manufacturers.

Dr Lisa Dean and her colleagues at the United States Department of Agriculture's Agricultural Research Service (USDA-ARS) have been investigating the metabolite profiles of popular peanut varieties produced in the US, and how these relate to flavour and other attributes. Their USDA-ARS unit represents the only public research program investigating peanut quality from a food science perspective. Through their research, Dr Dean and her team aim to assist in the development of peanut cultivars and processing methods that enhance the final flavour and preserve the marketability of US peanuts.

Metabolite Composition

Much like fine wines, each peanut variety possesses a unique flavour profile. Peanut varieties can be categorised into four main market-types: runner, Spanish, Virginia, and Valencia. The metabolite profile of each peanut strain determines the attributes important to food manufacturers and consumers. As such, the market-type selected depends largely on their intended usage. In the USA, runner and Virginia peanuts together account for 95% of the total peanut production, with runner peanuts particularly favoured for peanut butters and the larger Virginia peanuts often selected for processing into roasted and salted snacks.

In the first study of its kind, Dr Dean and her team investigated the metabolites found in raw runner and Virginia peanuts with the aim of identifying new avenues to improve the flavour, texture, roastability and storage life of these market-types. Using advanced analysis techniques, they identified 365 individual metabolites within the peanuts, with 52 of these differing significantly between the two market-types.

Their findings illuminate the source of some of the differences in the properties of the market-types. For example, a group of four vitamin E compounds, called 'tocopherols', showed the greatest differences between the market-types. As these metabolites are produced in the plant as a response to certain stressors, this suggests that different market-types have differing stress responses.

Many of the metabolic activities within peanuts, as with other plants, involve more than one type of compound. Thus, the selective breeding of new peanut varieties with a change in the abundance of one metabolite may also exhibit changes in the abundance of others. Breeding peanut strains with increased levels of 'oleic acid' – a healthy fatty acid – helps to improve their shelf life and flavour. However, because the production of oleic acid uses some of the same cellular processes as the production of tocopherols, a change in one may impact the levels of the other.

The Importance of Oleic Acid

In addition to oleic acid, peanuts also contain the fatty acids 'linoleic acid' and 'palmitic acid', with the former two being of particular interest to food manufacturers. Oleic acid helps to slow the natural degradation process in the peanuts, and thus helps to prevent 'flavour fade' (the loss of roasted

peanut flavour) and the development of stale flavours similar to cardboard or paint. Confectioners favour these 'high-oleic' peanuts because they greatly extend the shelf life of manufactured food products. Additionally, oleic acid is a major component in olive oil and consequently, peanuts containing higher levels of this fatty acid share similar health benefits with this popular oil.

As the production of these fatty acids in peanuts rely on shared cellular pathways, an increase in oleic acid depends on a decrease in the relative proportion of linoleic acid. Thus, peanut farmers and food manufacturers often use the ratio of these two metabolites to describe peanut varieties. With the development of high-oleic peanut strains, industry standards for many food products now require an oleic to linoleic acid ratio (O/L) of 9.0 or more, with some reaching ratios as high as 40. In comparison, traditional varieties have O/L ratios around 1.5–2. While improved peanut strains generally surpass the expected ratio, there is still a prevalence of peanuts with normal levels of oleic acid contaminating batches that should only contain high-oleic peanuts.

Dr Dean and her team investigated how these fatty acids develop across the growth period of runner and Virginia peanuts, for both normal and high-oleic varieties. They suggest that although some contamination is due to physical mixing of peanuts during processing, the growth pattern of the peanut plants themselves is largely to blame for the contamination. By sampling peanuts throughout their growth, Dr Dean demonstrated that the levels of oleic acid increased in high-oleic peanuts as they developed, with early samples having O/L ratios of around 4 – far below the industry standard. However, from the middle of the growth period onwards, most of the high-oleic peanuts had exceeded O/L ratios of 9.

Peanuts exhibit 'indeterminate flowering', meaning that flowers do not develop and mature at the same rate on the plant. As such, Dr Dean suggests that the presence of peanuts with low O/L ratios in high-oleic peanut batches is due to individual peanuts developing later in the season and being harvested before they have reached maturity. Implementing strategies to avoid including immature peanuts in batches may offer a solution to reducing contamination levels.

In addition, Dr Dean and her team have been investigating the shelf life and physical properties of peanut oils possessing a range of O/L ratios. Using both advanced analytical tools and descriptive sensory testing, they demonstrated that flavour fade and the development of stale flavours are slowed with increasing levels of oleic acid. Using these measures, they determined that peanut oils with the highest O/L ratio of 33.8 had a shelf life seven times higher than oils with the lowest O/L ratio of 1.3.

Identifying the rate of degradation in peanuts with differing O/L ratios is particularly important to food manufacturers, who use this information to select appropriate peanut varieties and determine the recommended shelf life of their products.

Optimising Roasting

In addition to the market-type playing an integral role in peanut flavour, the methods used to process them also contribute to the final flavour achieved. Most of the peanuts produced in the US are roasted before consumption, so a better understanding of how temperature and roasting time affect peanut flavour profiles is important for food manufacturers to optimise their production methods.

Dr Dean and her team investigated roasting parameters using a specialised oven that mimics the properties of the commercial-scale ovens used by food manufacturers. The amount of roasting is generally measured by a visual inspection of the colour of roasted peanuts: light, medium or dark. However, the required level of roasting can be achieved at a range of temperatures, with an increase in roasting time compensating for a lower roasting temperature and vice versa.

Of the five temperatures tested, medium-coloured peanuts roasted at a temperature of 177 degrees Celsius for 15 minutes developed the best flavour profile for jumbo sized runner peanuts. However, Dr Dean and her team also demonstrated that roasting parameters can be optimised based on other desirable characteristics. For example, they demonstrated that dark roasted peanuts had higher levels of vitamin E than light or medium roasted peanuts, but a decreased spreadability when used in peanut butters and pastes.

Towards Improved Peanut Varieties

By contributing to the understanding of how metabolites impact the overall flavour and properties of peanuts, Dr Dean and her team are aiding in the development of new peanut strains, as well as aiding food manufacturers in selecting the most suitable variety and processing methods. However, their pioneering work is only the beginning.

'These studies represent initial attempts to obtain compositional information about peanuts that was previously unreported,' concludes Dr Dean. 'As these studies are the start of using a powerful technique to fully characterise the metabolite profiles of raw and roasted peanuts, the research needs to continue.'

Meet the researcher

Dr Lisa L. Dean
Market Quality and Handling Research Unit
USDA-ARS
Raleigh, NC
USA

Dr Lisa L. Dean earned her PhD in Food Science with a Nutrition minor from North Carolina State University, after working for nine years as a Senior Food Chemist in a contract laboratory. Since receiving her doctorate, Dr Dean has held the position of Food Technologist in the Market Quality and Handling Research Unit at the USDA-ARS, which is the only ARS unit that performs food science research on peanuts. In addition, she serves as Courtesy Professor in the Department of Food, Bioprocessing and Nutrition Sciences at North Carolina State University. Through her research, Dr Dean and her team aim to improve the quality, shelf life, and value of USA peanut crops using chemistry and sensory analysis.

CONTACT

W: www.ars.usda.gov/people-locations/person/?person-id=21325
E: Lisa.Dean@usda.gov

KEY COLLABORATORS

Keith W. Hendrix and Dr Timothy H. Sanders, Market Quality and Handling Unit, USDA-ARS
Dr Claire M. Eickholt, General Mills Corporation
Dr Suzanne D. Johanningsmeier, Food Science Research Unit, USDA-ARS
Dr Jack P. Davis, JLA Global
Dr Xiaolei Shi, Iowa State University

FUNDING

The Peanut Institute, Albany, GA
The Peanut Foundation, Alexandria, VA
The Peanut Board, Atlanta, GA

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SUSTAINABLE FARMING

ENHANCING ECOLOGICAL HEALTH THROUGH SUSTAINABLE AGRICULTURE

Our second section celebrates scientists who are addressing one of today's most urgent research challenges: improving the sustainability of farming in the face of climate change and an ever-growing human population.

With about half of Earth's habitable land already used for human food production, at the expense of natural ecosystems, many of these researchers are developing new ways to grow food more efficiently, rather than continuing to convert the planet's remaining wilderness areas. Most of our featured scientists are also working to identify environmentally friendly approaches to farming, such as reducing our reliance on agrochemicals and focusing on soil health, so that biodiversity can thrive alongside our crops and livestock.

Our first few articles in this section focus on agricultural pest control. Such pests are responsible for devastating crop losses every year, greatly reducing the sustainability of food production. Furthermore, in an attempt to control pest populations, farmers are often inclined to apply large quantities of pesticides, with devastating impacts on local biodiversity. With the rise of pesticide resistance in many common insect pests, new solutions to pest control are urgently needed.

First up is Dr David Mota-Sanchez and his colleagues at Michigan State University, who are creating a worldwide, online database of pesticide resistance cases, to catalogue the scale of the problem. Cataloguing cases of resistance from all over the world since 1914, the 'Pesticide Resistance Database' will aid decision makers in developing sustainable strategies to manage insect pests.

Next, we meet Dr Joel Coats and his team at Iowa State University's Department of Entomology, who have been investigating essential oils as environmentally friendly alternatives to conventional pesticides. Many plants produce essential oils to defend themselves against insect pests, and as Dr Coats' research has shown, these natural compounds could represent a vital tool for overcoming pesticide resistance.

Continuing on the theme of sustainable pest control, we then feature the research of Dr Bryce Falk at the University of California, Davis, whose team has been developing new gene technologies to target a group of plant-feeding insects called psyllids. Psyllids are notorious for transmitting devastating diseases to agricultural crops, including Huanglongbing disease of citrus trees and zebra chip disease of potatoes. The team's aim is to develop targeted, effective, and environmentally sustainable methods for alleviating the devastating impacts of these diseases.

On the topic of plant diseases, our next article focuses on two fungal pathogens that impact basil crops across the globe – basil downy mildew and fusarium wilt. When basil downy mildew first emerged in the US in 2010, no sweet basil varieties were resistant to the disease, and growers began relying heavily on fungicide application to avoid devastating crop losses. Dr James Simon at Rutgers University, who we first met in the previous section, had been researching basil genetics for 25 years and was eager to tackle

this problem. Now, his team has successfully developed 12 new varieties of sweet basil that possess genetic resistance to downy mildew and two varieties with resistance to fusarium wilt disease.

Also researching plant genetics is Dr Elizabeth Cooper at the University of North Carolina at Charlotte. We highlight how her team has generated a full reference genome for a sweet sorghum cultivar called 'Rio', with the aim of understanding the genetic differences between sorghum varieties. Their research could provide a vital tool for biologists and breeders to improve sweet sorghum, which is an important crop in the US and India for food, animal feed and biofuel.

In addition to disease and pests, weeds are also a significant problem for crop farmers. However, heavy herbicide applications used to irradicate weeds can have damaging impacts on the environment. Therefore, Dr Rakesh Chandran and his team in the Agriculture and Natural Resources Department of West Virginia University have developed a more sustainable herbicide application regime that allows weeds to coexist with corn crops. Their approach has been shown to improve environmental health without significantly sacrificing crop yield.

From here, we shift our attention to soils, by first speaking with Professor Sacha Mooney, President of the British Society of Soil Science. In this exclusive interview, Dr Mooney describes the great importance of soil science research, both in the context of agriculture and natural ecology, and the varied ways that the Society advances this diverse and fascinating field.

Switching to agricultural practices that support beneficial soil microbes, and thus healthy soils, may help farmers achieve the yields required for continued food security. This is a significant focus of Dr Zachary Senwo's research at Alabama A&M University. In the first of his projects that we'll feature, his team is investigating soil nitrogen cycling and the role of microbes in soil health.

These soil microbes produce enzymes that can break down larger nutrient compounds into usable forms, which plants can then absorb through their roots. Therefore, Dr Senwo dedicates a significant proportion of his research to understanding these tiny machines. In the next article of this section, we feature another one of his fascinating projects, in which his team is uncovering the potential of enzymes towards informing new, sustainable agricultural practices.

Indeed, a deep understanding of soil ecology is vital for developing the most effective regenerative farming methods. Regenerative agriculture holds promising solutions that could help to restore and maintain healthy ecosystems and contribute to climate change mitigation, while keeping pace with food demands and enhancing farmers' resilience to environmental stress. However, encouraging farmers to adopt such sustainable practices can be challenging. Therefore, Dr Hannah Gosnell, who we meet next, aims to understand

what motivates cattle and sheep farmers to adopt and sustain the use of regenerative practices, while identifying the challenges that need to be overcome. Her work is informing efforts that incentivise farmers to transition to these methods.

Also working to make farming more sustainable, but taking a technological approach, is Dr Bruno Basso from Michigan State University. His team has been exploring how digital technologies, including sensors, satellites and drones, combined with data science and modelling tools, could usher in a new era of sustainable agriculture.

Next, we meet Dr Luis Tedeschi and his colleagues from Texas A&M University, who also explore the power of data science and computational modelling to increase the efficiency of livestock farming, while minimising environmental impacts. Dr Tedeschi hopes that his team's models will become a core component of smart farming applications, including automatic feeding systems and sensing technologies for disease detection. Our next article takes a very different perspective on smart agriculture, amongst other diverse areas. Here, we feature the fascinating research of Dr Stefan Rieger and Dr Ina Bolinski from the Ruhr-University Bochum, who take a 'multispecies approach' and show how scrutinising the collaborations between various species in a system could become key to solving many societal challenges, particularly in the area of smart farming. One aspect of their work focuses on sensors that can provide information about the condition and health of farm animals.

Early disease detection is also a large component of Dr Adelumola Oladeinde's research at the US Department of Agriculture, which we feature next. His team is currently developing the vision-based Salmonella Predictor (vbSALP) for poultry flocks, which uses advanced imaging technologies to collect information on poultry health and social cues associated with Salmonella infection. Another important aspect of his research has revealed the importance of the poultry microbiome in preventing infection from antibiotic-resistant Salmonella.

Dr Kenneth Overturf is another scientist with a keen interest in preventing disease in animals, and also understands the importance of the microbiome. His team at the USDA's Agricultural Research Service breed rainbow trout and develop nutritious, eco-friendly feeds, with the aim of improving disease resistance and muscle growth, towards boosting global fish production in a sustainable manner.

In our final article of this section, we introduce Dr David Welch and his team from Kintama Research Services Ltd, who are investigating the serious declines in Chinook salmon populations along the West Coast of the US. The team's new insights have significant implications for informing conservation strategies to protect and restore this important species.

KNOWLEDGE IS POWER IN THE FIGHT AGAINST PESTICIDE RESISTANCE

First recognised over a century ago, the resistance of insects and other arthropods to pesticides is a growing problem, with implications for crop production and human health on a global scale. **Dr David Mota-Sanchez** and his team at Michigan State University are creating a worldwide, online database of resistance cases to catalogue the scale of the problem. Their work will aid decision makers in developing sustainable strategies to manage arthropod pests.

Pesticide Resistance

From the production of potatoes and rearing of livestock, to eradicating head lice and reducing cases of malaria – solving the problems created by arthropod pests has everyday applications that most of us have probably never realised.

Arthropods are invertebrates with an external skeleton, segmented body and jointed legs. They are divided into four groups: insects, myriapods (including centipedes and millipedes), arachnids (including spiders and mites) and crustaceans. Arthropods play major roles in maintaining ecosystems, where they act as pollinators, nutrient recyclers, scavengers and food for other animals. However, many are also significant pests that threaten agricultural systems, human health and animal health. This problem has become even greater due to the growing resistance of many arthropod species to the pesticides used to control them.

Resistance, or 'field-evolved resistance', is the micro-evolutionary process whereby exposure to a pesticide promotes genetic adaptation, resulting in populations of arthropods that are less vulnerable to that pesticide. Such reduced vulnerability, or 'practical resistance', to a given pesticide might result in a loss of pest management tools for current and future generations.

Furthermore, if certain chemical pesticides are overused and misused, they can have detrimental impacts on the environment and human health. Specifically, increased pesticide usage can have a negative impact on non-target species, and consequently, the biodiversity of the wider environment. These non-target species may include pollinators or natural enemies of the targeted pests. In addition, high levels of pesticide residues might end up in food, soil and water.

A Database of Knowledge

Estimates of the impact of pesticide resistance on crop production suggest losses of between $1.4 and $4 billion to the US economy annually. However, the danger that resistance poses goes well beyond this economic impact. In the face of a growing global human population, the crop damage caused due to pesticide resistance has significant implications for food security. Dr David Mota-Sanchez and his team at Michigan State University recognised that without better record keeping and resistance severity assessments, the worldwide impact of pesticide resistance might never be fully understood.

'The Arthropod Pesticide Resistance Database is perhaps one of the most complete databases tracking pesticide resistance cases from all over the world since 1914. It shows us that up until now, arthropods have developed resistance to more than 349 compounds, and there are now more than 17,000 cases of resistance amongst 612 species globally.'

Published cases of pesticide resistance have grown in frequency since the start of the twentieth century, when scientists first began to question whether insects could become resistant to chemical sprays. However, up-to-date records were not readily available or accessible to a global audience. With this in mind, Dr Mota-Sanchez and his predecessors began to develop a database that could offer information from anywhere in the world, while nearly instantaneously updating and reporting the world's arthropod resistance status. They started by carrying out a comprehensive review of all of the reported cases of resistance over the last 100 years. They then developed criteria to categorise resistance levels, and compiled the results of their review into a new online system, to which new records could be quickly and easily added. As a result of their efforts, the Arthropod Pesticide Resistance Database was born.

'The Arthropod Pesticide Resistance Database is perhaps one of the most complete databases tracking pesticide resistance cases from all over the world since 1914,' says Dr Mota-Sanchez. 'It shows us that up until now, arthropods have developed resistance to more than 349 compounds, and there are now more than 17,000 cases of resistance amongst 612 species globally.'

Importantly, the database will go beyond simply providing a platform for reporting of resistance incidence. It will also deliver a mechanism by which experts can share resistance management strategies, tactics and tools to promote better agricultural production, human and health, international cooperation and scientific progress.

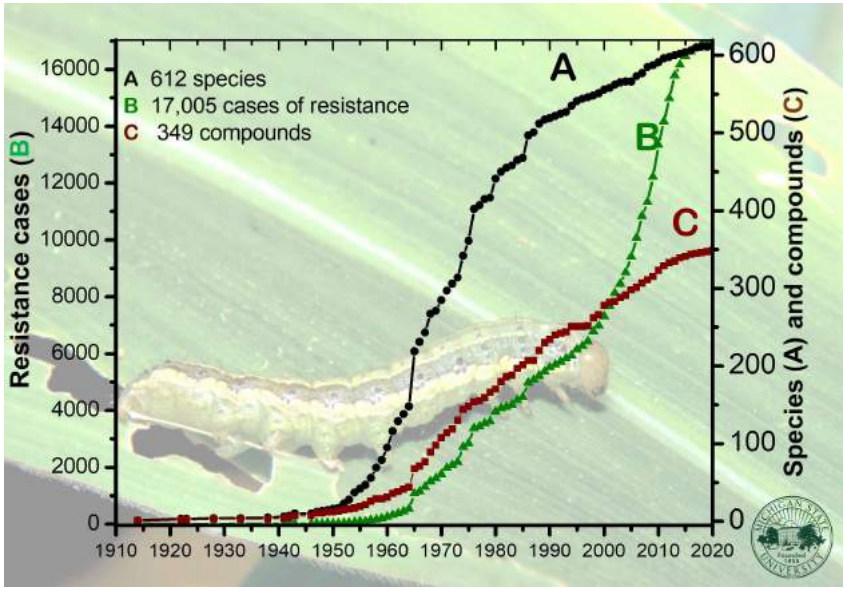
Dr Mota-Sanchez and his team urge researchers to publish their resistance monitoring data in conjunction with data on management practices. This will accelerate progress in determining the most useful actions in response to specific data on the magnitude, distribution and impact of resistance.

The Battle Against Fall Armyworm

The team's research into a moth species called the fall armyworm demonstrates how increased knowledge of the mechanisms behind pesticide resistance can be used to inform the development of new pest management strategies. Fall armyworm is one of the main pests of corn in many areas of the American continents. As with many other examples, a reliance on pesticides to control fall armyworm has led to the development of resistance.

Dr Mota-Sanchez and his graduate students Rebeca Gutierrez-Moreno and Omar Posos determined the resistance levels of the fall armyworm to different types of pesticides in populations from Puerto Rico and Mexico. They found that in particular, the Puerto Rican populations showed a remarkable resistance to pesticides with many different modes of action, whereas populations in Mexico showed varying levels of susceptibility to different compounds – possibly as a result of the heterogeneity of pest management patterns in the country.

In Puerto Rico, the team found that the pest is still resistant to two Bt proteins. Bt crops are those that have been genetically engineered to contain a *Bacillus thuringiensis* (Bt) gene that encode a Bt protein, which offers the plants protection against the fall armyworm. This finding had significant implications for controlling the fall armyworm in the countries where Bt crops are deployed.
In late 2018, the fall armyworm was discovered in Myanmar for the first time, where it has the potential to create short and long-term impacts on crop production. Dr Mota-Sanchez and a Michigan State University delegation collaborated with the Department of Agriculture in Myanmar, to help reduce



Evolution of arthropod pesticide resistance from 1914 to 2020. D Mota-Sanchez, and JC Wise, 2020, The Arthropod Pesticide Resistance Database: www.pesticideresistance.org

the pest's impact by utilising the lessons learned from their research in Puerto Rico and Mexico.

Fall armyworm populations have now also been discovered in neighbouring countries in the region, including Bangladesh, Thailand, China, Indonesia and Australia, and the sustainable management practices implemented and investigated in Myanmar could help to reduce the impact of the pest in these countries as well. The Arthropod Pesticide Resistance Database provides the mechanism for recording and sharing this information at a global scale, to benefit all parties involved.

An Integrated Approach

Dr Mota-Sanchez also collaborated with colleagues from Mexico to study the impact of the long-term use of Bt cotton in Mexico. Prior to the use of Bt cotton in Mexico, it was common for cotton fields to be sprayed with pesticides up to 18 times in a single season. Even with such an intensive application regime, growers still lost more than 30% of their potential yield, mainly due to pests that were highly resistant to pesticides. Since the introduction of Bt cotton more than 20 years ago, pest management in the country's cotton industry has changed substantially. Growers use around 50% less pesticide and are no longer worried about the insects that previously damaged their yields.

As a result of their research, the collaborators concluded that the high adoption of Bt cotton in Mexico, as part of an Integrated Pest Management (IPM) program, has preserved the susceptibility of insect pests to the Bt toxin, allowing cotton yields to increase for more than two decades.

Aside from the use of genetically engineered crops, there is a huge range of new and old resistance avoidance strategies, tactics and tools available for today's crop farmers. However, in many cases, those who make treatment decisions probably only choose a single tactic – usually pesticide applications – to limit the damage caused by pests. Dr Mota-Sanchez warns that the sustained use of a single tactic continues to promote resistance.

'The adoption of many tactics is similar to a chess game,' he describes. 'The movements of all the pieces on the board matter and must be coordinated to win the game. Even a pawn can make small favourable contributions. If a chess player carelessly displays the queen, the most powerful piece in the board, the opponent can defeat the player. In pest management, the situation is analogous, if we overuse and expose a particular tactic, such as insecticides, the result is the loss of these tools. Insects have a long history of overcoming pest management insecticides by developing enzymes to metabolise compounds or mutations at the target sites, rendering them innocuous.'

The IPM and Integrated Resistance Management (IRM) approaches that he advocates can reduce the potential for resistance simply by diversifying the mortality mechanisms triggered in target pest populations. IPM and IRM strategies can include the use of newly developed pesticides with novel modes of biochemical action, together with other techniques such as rotations, introducing natural enemies of the pest, the use pheromones, host plant resistance, and the use of refuge to produce susceptible pest individuals.

The development of more diverse strategies for pest control will become ever more necessary as tighter regulations might reduce the use of some insecticides. Even in the absence of government restrictions on insecticide use, management of arthropod populations by chemical means relies on our ability to discover new mechanisms and develop new chemicals at pace. Indeed, in the resistance arms race, the rate of arthropod evolution might outstrip our ability to replace outmoded chemicals.

To avoid this, and alongside an IPM and IRM approach that allows us to preserve the effectiveness of new technologies, we must also address the mix of ecological, genetic, economic and socio-political factors that will improve the implementation of sustainable pest management practices. The Arthropod Pesticide Resistance Database has a pivotal part to play in providing the information and background necessary to implement such an approach, and will have a key role in the future of pesticide resistance management.

Meet the researcher

Dr David Mota-Sanchez
Department of Entomology
Michigan State University
East Lansing, MI
USA

Dr David Mota-Sanchez gained his PhD in the Department of Entomology at Michigan State University. Here, he is currently an Assistant Professor of Entomology, where his research focuses on the evolution of arthropod resistance to xenobiotics, insecticide toxicology and resistance of arthropods to xenobiotic compounds. The major insect pests he has worked with include Colorado potato beetle, fall armyworm, western flower thrips, codling moth and oblique banded leaf roller. He has also worked on the impact of insecticides on the environment and the movement of pesticides in plant tissues. He is co-Director of the Arthropod Pesticide Resistance Database, which tracks cases of arthropod resistance globally, dating back to 1914. Dr Mota-Sanchez also served as an Embassy Science Fellow with the US State Department and USDA FSA in Mexico to increase awareness and understanding of genetically engineered crops, and is involved in training farmers in Integrated Pest Management. He is also involved in an extension project to train first and next generation of Latino farmers in Michigan, in addition to a research and extension program focusing on the monarch butterfly in Michigan and Mexico.

CONTACT

E: motasanc@msu.edu
W: www.canr.msu.edu/people/david_mota_sanchez

KEY COLLABORATORS

John Wise, Michigan State University
Barry Pittendrigh, Michigan State University
Living with Resistance Project: PS Jørgensen, A Aktipis, Z Brown, Y Carriere, S Downes, R Dunn, G Epstein, GB Frisvold, D Hawthorne, Y Grohn, G Tikaramsa, D Jasovsky, E Klein, G Lhermie, D Mota-Sanchez, C Omoto, M Schlüter, MH Scott, D Wernli, SP Carroll

FUNDING

The Insecticide Resistance Action Committee (IRAC) Generating Research and Extension to meet Economic and Environmental Needs (GREEEN) Project (Ag Bioresearch Michigan State University)

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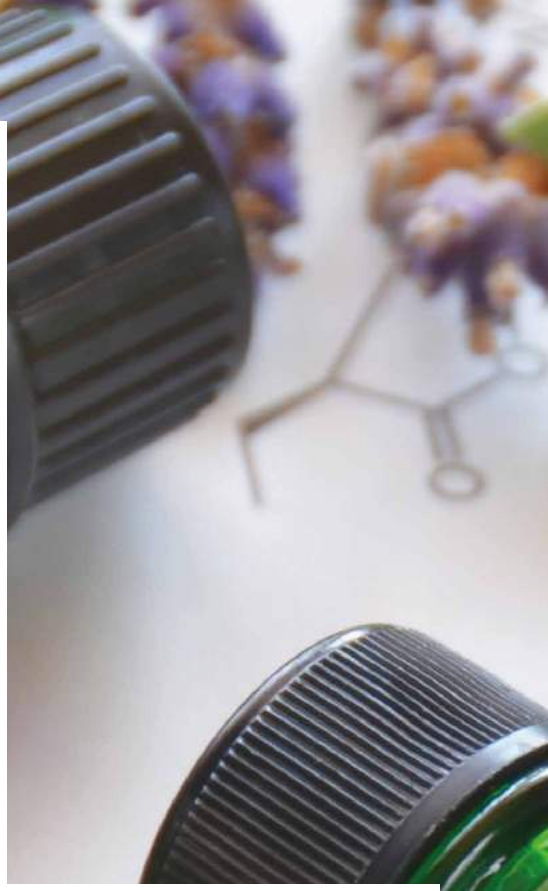
MICHIGAN STATE UNIVERSITY

NATURAL ESSENTIAL OILS AS NOVEL PESTICIDES

Insect pests cause devastating economic losses in agriculture, and as vectors of disease they have significant impact on the health of humans, livestock and pets. Plant essential oils have been used for centuries as protection against insect pests, but scientists have only recently begun to explore the extent of their potential for pest control. **Dr Joel R. Coats** and his team at Iowa State University's Department of Entomology have been investigating essential oils as greener alternatives to conventional pesticides, and as a vital tool for overcoming pesticide resistance in insect populations.



The Need for New Pesticides

Whether you love them or hate them, insects are an indispensable part of life on our planet. These ubiquitous creatures form the most abundant, diverse and successful group of animals on Earth, with some estimates suggesting that for every human, there may be over a billion individual insects.

The majority of insect species have very little impact on humans, and many are even vital for our continued existence, providing valuable services such as pollinating our food crops, recycling nutrients and acting as a food source for larger animals. However, a small minority of insect species have the capacity to have utterly devastating impacts on individuals and communities, including causing widespread damage to our crops or spreading deadly diseases.

Conventional synthetic pesticides and insect repellents have played an important role in defending crops, humans, livestock, pets and property from invading pests, but these chemicals are not without their own suite of problems. Pesticide resistance is increasing in prevalence and threatens to render some of the most widely available chemicals ineffective. Many of these pesticides also have harmful effects on natural ecosystems and non-target species, and persist in the environment far from their target location. These serious problems mean that alternative methods of controlling pests need to be safer for humans, pets, livestock, non-target insect species and the surrounding environment.

Essential Oils

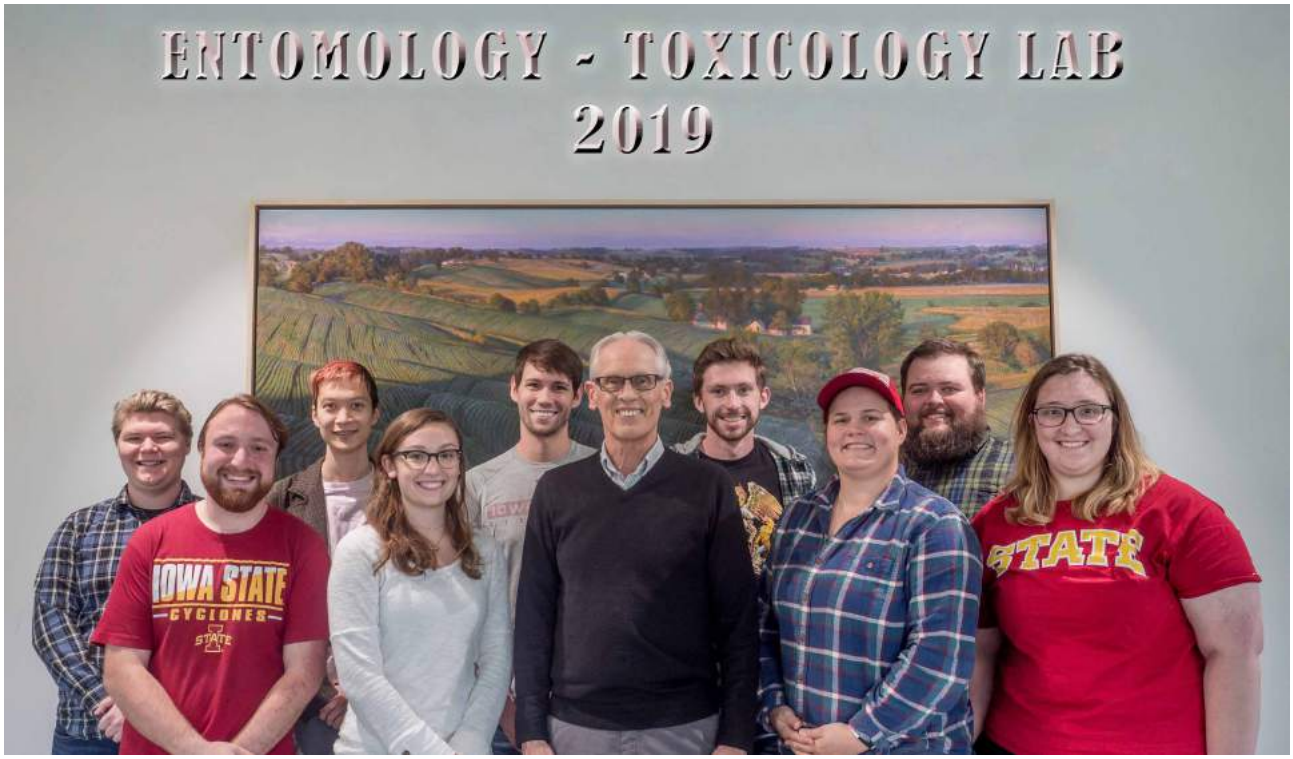
Many of the plant aromas that humans find so irresistible are actually produced by the plant as a natural defence against insect pests. Thus, these natural substances offer an innovative avenue for the development of new pesticides and insect repellents. People have used concentrated fragrant plant compounds for centuries, in the form of essential oils, to help deter unwelcome insects, but until recently, many of these natural alternatives have remained largely unexplored by scientists.

Dr Joel Coats and his team in the Department of Entomology at Iowa State University have been investigating plant essential oils and their potential as effective alternative pesticides and insect repellents. Through their exciting new research, they have demonstrated

that many of these plant essential oils may also act in synergy with synthetic pesticides, increasing their effectiveness on target insect species, and thus may help to counteract some instances of pesticide resistance.

Moving Towards Green Chemistry

The development of synthetic pesticides, such as pyrethroids (used in crop fields and found in many household pesticides) and DEET (used to repel biting insects), has allowed agriculture to keep up with the food requirements of a growing population and helped protect humans from diseases spread by blood-feeding insects.



However, these pesticides are not without undesirable effects. Pyrethroid resistance has been discovered multiple times in pest populations and poses a significant risk to the continued efficacy of this group of chemicals. DEET has an unpleasant smell and is known to corrode plastics found in sensitive equipment and some synthetic fabrics. Both DEET and pyrethroid compounds can also be harmful to human health.

The disadvantages of these chemicals and other conventional pesticides have encouraged a move towards 'Green Chemistry' – the design, manufacture and use of alternatives to the chemicals currently available. 'Green chemistry indicates that a chemical is natural, but it also implies that it is safe for humans and pets, non-toxic in the environment, and rapidly and fully biodegradable,' explains Dr Coats.

Plant essential oils are ideal candidates for investigation in Green Chemistry. These substances are generally produced by plants to deter hungry pests, and are far less harmful to humans, animals and the environment. Many of these essential oils are already widely used, in fragrances, foods and beverages, aromatherapy, and in pharmaceutical medications.

Essential oils such as citronella, rosemary, cinnamon, mint and clove oils have been used as repellents against mosquitoes and other biting insects for centuries. Spatial repellents, which curb the approach of mosquitoes, and contact repellents, which deter landing and biting when used on the skin, are both important methods for preventing mosquito bites and thus the spread of mosquito-borne diseases.

However, it is only relatively recently that scientists have discovered that the effects of these natural chemicals on insects is not purely repellent. Many of these fragrant compounds disrupt the nervous system and the physiological processes of insects, causing toxic effects in the correct concentration. Dr Coats and his team suggest that a greater understanding of the mechanisms behind the toxic action of these natural chemicals on insects will aid the development of novel alternatives to conventional pesticides and repellents.

Essential Oils as Mosquito Repellents

Mosquitoes remain one of the greatest threats to human and veterinary health, transmitting a range of debilitating pathogens which cause the death of around 700000 people each year. Resistance or insensitivity to both contact and spatial pyrethroid-based repellents have been recorded in mosquitoes, posing a significant risk to the continued effectiveness of these currently used chemicals.
Dr Coats and his team have been investigating the repellency of plant essential oils with the aim of identifying suitable alternatives. 'From these explorations, a wide range in efficacy has been identified among various plant compounds as spatial and contact repellents,' says Dr Coats.

Thus far, some of his team's most promising results have come from a group of fragrant plant compounds called terpenes. These plant terpenes, which include the fragrant components of citronella oil and thyme oil, are very effective for a short period after application, but their effectiveness declines drastically after a few hours, as the fragrances dissipate into the surroundings.

‘After studying natural repellents for 20 years, we have designed, synthesised, and evaluated synthetic analogues of the best terpene repellents, termed biorational repellents. They represent a third major class of repellents for development against disease-carrying pests such as mosquitoes and ticks.’

By slightly altering the natural plant terpenes, such as using advanced techniques to decrease the speed at which they dissipate, Dr Coats was able to improve the long-term repellency of these substances. ‘After studying natural repellents for 20 years, we have designed, synthesised, and evaluated synthetic analogues of the best terpene repellents, termed biorational repellents,’ he says. ‘They represent a third major class of repellents for development against disease-carrying pests such as mosquitoes and ticks.’

The success of this approach may open opportunities to increase the longevity and efficacy of other plant essential oils, and to increase the efficacy of the current commercially-available pesticides and repellents.

Essential Oils as Pesticide Synergists

In some of their most recent work, Dr Coats and his colleagues have demonstrated the potential for plant essential oils to act in synergy with pyrethroid-based pesticides to increase their effectiveness against mosquitoes. Among the tested essential oils were patchouli, clove, Texan and Moroccan cedarwood, basil, oregano, geranium and cinnamon. When mixed with various types of pyrethroid-based pesticides, many of these essential oils increased the mortality rate of the dengue and Zika virus-transmitting *Aedes aegypti* mosquito.

However, some of these essential oils were better than others at increasing the toxicity of the pyrethroids, for example patchouli and Texan cedarwood, and the concentration of the added essential oil had a significant impact on its effectiveness. Dr Coats and his team suggest that particular terpenes within these essential oils act to inhibit the mosquitoes’ natural detoxifying processes, preventing them from flushing the pyrethroid chemicals out of their systems quickly enough. In pest populations where an increase in detoxifying abilities represents the basis of pesticide resistance, the action of these essential oils may act to counteract this resistance.

Additional investigation is required to confirm the actions of terpenes within insect physiological processes and to identify additional essential oils to use as pyrethroid synergists. ‘Although these results provide promising leads for the use of plant essential oils to synergise pyrethroids in formulation, further work must be completed to fully implicate plant essential oils as inhibitors of various detoxification processes, or their capacity for up-regulating or down-regulating insect genes,’ says Dr Coats.

Novel pesticide formulations are prohibitively difficult to develop and get approved. Therefore, increasing the effectiveness of pre-existing pesticides through natural additives may provide a valuable alternative approach. ‘Plant essential oils could be included in spatial sprays and in indoor residual spraying campaigns, but further work is required to better understand how these chemistries should be formulated into future control products and technologies, and how these formulations act in other mosquito strains,’ explains Dr Coats.

Dr Coats and his team are continuing their investigations of novel pesticides and insect repellents, indicating that even better solutions are on the horizon. ‘We are now studying a new type of natural molecule from a plant oil that is more potent than the terpenes, and we have synthesised a series of analogues of it,’ he concludes. ‘We believe it has a novel mechanism of action against insects.’

Meet the researcher

Dr Joel R. Coats
Department of Entomology
Iowa State University
Ames, IA
USA

Dr Joel Coats earned his PhD in Entomology with a minor in Chemistry from the University of Illinois in 1974. He has since spent his esteemed career investigating the action and potential use of natural products as insect repellents and insecticides, and the persistence of agrochemicals in the natural environment. He currently holds the position of Distinguished Professor of Entomology at Iowa State University, where he teaches and supervises undergraduate and postgraduate students alongside his research activities. Dr Coats has published over 200 articles in prestigious scientific journals, published numerous books and book chapters, holds multiple patents, and has been awarded many fellowships and other honours for his excellent contributions to science.

CONTACT

W: https://www.ent.iastate.edu/people/joel-coats
E: jcoats@iastate.edu

KEY COLLABORATORS

Steven P Bradbury, Entomology, Iowa State University
George Kraus, Chemistry, Iowa State University
Ke Dong, Entomology, Michigan State University
Steven Bessette, EcoSMART, Kittrich
Agenor Mafra-Neto, ISCA Technologies

FUNDING

Deployed Warfighter Protection Program (DWFP) of the US Department of Defense
Centers for Disease Control and Prevention

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FIGHTING PLANT DISEASE WITH VIRUS-BASED GENE TECHNOLOGY

Plant pathogens transmitted by insect vectors can have devastating consequences for farmers across the globe. Huanglongbing disease of citrus trees and zebra chip disease of potatoes are both caused by bacteria transmitted by specific psyllid insect species, and have the potential to destroy entire crops, causing enormous economic losses. Conventional control methods rely on pesticides, but these can have adverse effects on the environment. In addition, resistance to these chemicals is on the rise in many pest species. Dr Bryce Falk and his plant pathology team at the University of California, Davis aim to solve this problem by developing highly targeted psyllid control methods using virus-based gene technologies.

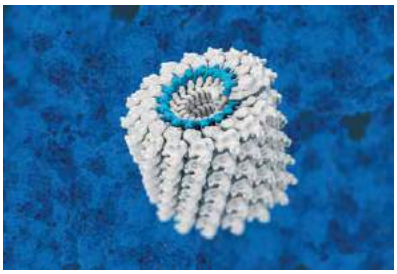
Viruses in Gene Technologies

Viruses are so tiny that you may only remember their existence when you develop that peculiar throat tickle that signals an impending cold. However, viruses are everywhere. As the most numerous microbes on the planet, they interact with every kind of organism, including bacteria and even other viruses. Recent estimates suggest that only a tiny fraction of the total number of viruses have been discovered so far. Many viruses do not cause disease in their hosts, and thus it is only with recent technological advancements that these unknown viruses have begun to be discovered.

Most viruses are highly adapted to a small number of potential hosts, sometimes only infecting a single host species. They multiply by hijacking the processes within the host's own cells, forcing them to make new virus particles. Their method of replication, along with their susceptibility to manipulation by gene technologies, makes viruses valuable tools to transfer desirable characteristics directly to the cells of their hosts.

Virus-mediated gene technology shows tremendous promise in agriculture. Using precisely altered viruses, desirable traits such as resistance to pests or diseases can be conferred to plants. Conventionally, farmers have relied on the use of insecticides to control pest insect populations, while using antibiotics and fungicides to treat plant diseases caused by bacteria and fungi, respectively. However, these chemicals have a tendency to find their way into the surrounding ecosystem and can be damaging to non-target species, such as beneficial insects. Furthermore, many pest insect species have started developing insecticide resistance, which threatens to render the current control methods ineffective.

Gene technologies offer a highly specialised solution to this problem. When combined with particular viruses, this technology has the potential to be harmless to the surrounding environment and non-target insects.



Dr Bryce Falk and his team in the Department of Plant Pathology at the University of California, Davis have devoted years to investigating the use of viruses to control agricultural plant pests and diseases.

In their recent work, Dr Falk and his team have been developing new virus-mediated gene technologies to target psyllids – a group of plant-feeding insects known commonly as 'jumping plant lice' – and the diseases caused by the pathogens that psyllids transmit to agricultural crops. Their aim is to develop targeted, effective, and environmentally sustainable methods for alleviating the devastating impacts of these notorious pests.

Virus-based Psyllid Control

In moderate numbers, psyllid species themselves often cause little more than an unsightly nuisance. However, psyllids are ideal vectors – or transporters – of microbes that cause diseases and even death in plants. These insects use their needle-like mouthparts to feed directly from the nutritious fluids inside the plant, and thus provide a perfect route for pathogens (disease-causing microbes) to be spread between plants. The pathogens transmitted by specific psyllids are often devastating, rendering entire crops inedible and thus causing significant economic losses.

However, psyllids are selective about their food plants, and each psyllid species is usually restricted to a single host plant species or a small number of related plant species. This makes psyllids and their associated pathogens ideal candidates for highly targeted control methods such as those being developed by Dr Falk and his colleagues.

Dr Falk's team demonstrated the effectiveness of using viruses to target pest psyllids in previous work with the potato and tomato psyllid, *Bactericera cockerelli*, which transmits the bacterium that causes the zebra chip disease of potatoes. Using advanced gene technology, Dr Falk altered the Tobacco mosaic virus to negatively affect the potato psyllid.

The altered Tobacco mosaic virus spreads throughout the treated plants, causing the plant cells to produce RNA strands – fragments of 'genetic instructions' – that interfere with the cell functions of the potato psyllid. As the psyllids feed on the treated plant, the strands of RNA travel through the psyllid's gut into their cells, interrupting normal cell processes that are integral to reproduction.

However, while this technique is an excellent method of testing new virus-mediated gene technologies, ingestion of the RNA is not an ideal route of delivery. In some cases, the effects produced by these RNA strands are limited to the insect gut. Additionally, refining and scaling up the technology, such as by producing plants with the desired gene alterations, is prohibitively expensive and time-consuming. To combat these limitations and improve the efficacy of their technology, Dr Falk and his team have been investigating the use of insect viruses instead of plant viruses.

Novel Psyllid Viruses to Control HLB

The recent discovery of many insect-specific viruses has provided a novel opportunity to develop targeted technologies to control pests and diseases in agriculture. Insect-specific viruses are superbly adapted to infecting their insect host species and spread naturally throughout the insect's body. 'In addition to targeting their insect hosts, insect specific viruses might be used for other goals, particularly for interfering with insect vector transmission of pathogens,' says Dr Falk. These insect-specific viruses provide the basis for improving the delivery of the interfering RNA strands to pest psyllids.

Dr Falk and his team have collected viruses of the Asian Citrus Psyllid, *Diaphorina citri*, from across the world with the aim of developing an effective and targeted technology to control their populations. The Asian Citrus Psyllid transmits the pathogenic bacterium that causes Huanglongbing (HLB) disease, also known as Citrus Greening Disease, causing devastating crop losses and often resulting in tree death. Currently, the main method of controlling the disease is by spraying with pesticides to manage the insect vector. However, this strategy is not sufficiently effective and pesticide resistance is increasing in the Asian Citrus Psyllid; therefore, finding an effective alternative control method is becoming increasingly urgent.

'We now know that the HLB psyllid vector naturally hosts many viruses as part of its microbiome,' explains Dr Falk. 'Psyllid-specific viruses are the ideal viruses to be used as tools in the field because they are not associated with plant or animal diseases, and due to their specificity to the psyllid target, avoid accidental transmission to beneficial insects.'

Development of Psyllid Virus Technology

Multiple potential strategies to use the collected viruses for new HLB control methods are being evaluated by Dr Falk and his team. The first strategy is to use one, or more of the viruses in combination, to induce negative effects in the psyllids and thus disrupt their ability to spread the HLB bacteria. The second strategy is to use gene technologies to alter the virus so that as it infects and spreads through the psyllid host's body, it tricks the psyllid's own cells into producing interfering RNA strands.

The potential effects of these psyllid-targeted genes include hindering movement, reproduction or other important behaviours, increasing mortality rates in the psyllid population, or disrupting the ability of the psyllid to transmit the plant pathogenic bacteria – for example by blocking the cell functions involved in the uptake and spread of the pathogen.

To optimise their gene technology, Dr Falk and his team are initially using two model insect viruses, the Flock House Virus and the Cricket Paralysis Virus, that are able to infect the Asian Citrus Psyllid. While these viruses are not the psyllid-specific viruses that Dr Falk aims to ultimately use in his HLB control method, they are highly amenable to gene alteration and provide an important starting point for identifying the psyllid cell processes that are most effectively targeted with the gene technology.

The model viruses can be produced in preparations of non-psyllid insect cells, and then purified before infecting psyllids to monitor the effects of the insect-targeted genes. This method allows Dr Falk and his team to produce sufficiently large numbers of the altered virus particles before testing them on their psyllid colonies. Monitoring infected psyllids over longer periods allows the researchers to ensure that the desired effects within the psyllids are reliable and long-lasting. 'It is not necessarily straightforward to choose which traits might be desirable and which would not lead to strong selection pressure to negate the efficacy of the approach,' Dr Falk explains.

Dr Falk and his team aim to produce a psyllid-specific virus-based control method that is easily incorporated into the current treatment cycles used by citrus farmers. By producing an effective and targeted HLB control that can be incorporated into the management strategies used routinely in citrus orchards, Dr Falk hopes the barriers to uptake of the technology will be sufficiently low. Additionally, in contrast to plant virus-based technologies, delivery of the psyllid viruses by ingestion is not likely to significantly lower their efficacy.

'From this project, we hope to deliver a functional psyllid-specific virus-based tool for citrus growers as a novel, rapid and more environmentally friendly strategy to help manage HLB,' Dr Falk concludes. Successful development of this technology for controlling the Asian Citrus Psyllid and the associated HLB disease may also provide a solid foundation for extending this insect virus-based technology to other agricultural pests and diseases.

Meet the researcher

Dr Bryce W. Falk
Department of Plant Pathology
University of California
Davis, CA
USA

Dr Bryce Falk earned his PhD in Plant Pathology from the University of California (UC), Berkeley, in 1978. Upon graduating, he worked as a postdoctoral researcher at UC, Riverside, followed by assistant professor at the University of Florida, before moving to UC, Davis in 1985. Here, he currently holds the position of Distinguished Professor in the Department of Plant Pathology. Dr Falk has devoted his decades-long career to investigating plant and insect viruses and the diseases they cause, and developing methods of controlling them. He has over 200 articles published in peer-reviewed journals, and his research has included the discovery of new viruses and the characterisation of numerous virus genomes. At UC, Davis, he also supervises and teaches many undergraduate students, doctoral candidates and postdoctoral researchers, in addition to his research activities. Dr Falk has held editorial positions for several esteemed journals, and has been awarded multiple fellowships and awards for his contributions to science.

CONTACT

E: bwfalk@ucdavis.edu

UCDAVIS
UNIVERSITY OF CALIFORNIA

KEY COLLABORATORS

Dr Elizabeth M. Henry, University of California, Davis
Dr Emilyn E. Matsumura, University of California, Davis
Dr Kristine Godfrey, University of California, Davis
Dr Yen-Wen Kuo, University of California, Davis
Dr Shahideh Nouri, Kansas State University

FUNDING

USDA-NIFA
USDA-APHIS-PPQ

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A BREAKTHROUGH IN THE WAR AGAINST BASIL DOWNY MILDEW

Sweet basil is among the most popular and economically important culinary herbs, but by 2010, US production began to feel the impact of a newly emerging destructive disease: basil downy mildew. At that time, no sweet basil varieties were resistant to basil downy mildew and growers began relying heavily on fungicide application to avoid devastating crop losses. **Dr James Simon** at Rutgers University had been researching basil for 25 years and was eager to tackle this problem. Eight years later, Dr Simon's team is proud to have successfully developed 12 new downy mildew resistant varieties of sweet basil and two varieties resistant to fusarium wilt disease.

A Devastating New Disease

Basil, belonging to the genus *Ocimum*, is the most popular herb purchased in the US. It is used primarily as a culinary flavouring, but is also an ornamental plant and a scent additive for household products and cosmetics. The most familiar variety, sweet basil (*Ocimum basilicum*), is extremely important, generating over $300 million in annual sales in the US alone, while providing numerous jobs for growers, farm labourers, packers, shippers, distributors and retailers. Cultivating basil was a relatively straightforward and profitable process until the newly emergent disease, basil downy mildew, was reported for the first time in the US in 2009.

The devastating fungus-like pathogen emerged in Europe in 2001 and then spread to the US, where it obliterates crops and causes tens of millions of dollars in economic losses. As injured basil leaves are unmarketable, some growers' entire crops were destroyed and many opted out of growing basil altogether.

Basil downy mildew (BDM) is dispersed by air-borne spores from infected leaves and seeds. Efforts to reduce its spread and severity had been thwarted by the absence of an effective seed treatment or chemical control method. Finding a viable, long-term, and economically sustainable solution to BDM has been a matter of great urgency for basil cultivators worldwide.

In 2010, Rutgers' Dr James Simon was ideally positioned to tackle this devastating pathogen, having dedicated a large portion of his distinguished research career to studying basil genetics and breeding. Dr Simon knew that the key to fighting this intensely damaging blight was to develop genetic resistance to the disease. So, his research team began the hunt for a variety of sweet basil with natural genetic resistance to BDM. This approach formed the pillar of their plant breeding strategy, which was ultimately incorporated into their integrated pest management plan.

Plant infected with basil downy mildew (BDM).

'Integration of downy mildew-resistant sweet basil cultivars into pest management strategies represents a more sustainable control strategy that is advantageous to environmental, public health, and economic interests,' says Dr Simon.

Searching for BDM Resistance

Earlier work by Dr Simon and his colleague, Dr Andy Wyenandt, the state's vegetable crops extension specialist in plant pathology, had shown that all commercial sweet basil cultivars were highly susceptible to BDM. They also found that some exotic and ornamental basils appeared to be entirely immune to the disease. Several of these exotic basil varieties, different species from sweet basils, exhibited a range of tolerance levels and what appeared to be immunity to BDM. Unfortunately, the exotic species have a different number of chromosomes to sweet basil, making cross-breeding very difficult.

Dr Simon's team spent several years manually cross-breeding hundreds of basil varieties from numerous species, with the goal of introducing only the BDM-resistant genes from the

'I have always loved basil. It is a beautiful, attractive plant with unique chemistries that offered me many creative opportunities to ask unique genetic and biological questions. Basil is also important to so many people, cultures and agriculture industries, so my successful work with this plant gives me the opportunity to positively impact others.' – Dr James Simon

Dr Simon and Dr Wyenendt in a field with one of their basil varieties, 'Rutgers Devotion DMR', in Clewiston, Florida.

exotic basils into sweet basils. In doing so, they faced a significant challenge. The hybrid plants were sterile, and while they each had many of the visual characteristics of a sweet basil variety, they lacked the aroma and taste that consumers enjoy.

To facilitate a swift search for BDM-resistant basils, Dr Simon and his team developed a technique to rapidly screen plants for their response to the pathogen under controlled conditions, as well as larger field screens to confirm purported resistance. They discovered that plants respond to BDM at their earliest growth stage when their first seed leaves appear, thus indicating the plant's susceptibility to the disease throughout its growth. Dr Simon's team knew that they needed to establish extensive, multi-year testing, in order to identify new varieties of BDM-resistant basil and to develop a series of families and advanced breeding lines upon which to build.

The BDM pathogen develops particularly well in humid conditions when leaves are wet for an extended period. Dr Simon's plan was to recreate the conditions that allow BDM to flourish, so as to accurately identify resistance. 'In the absence of adequate disease pressure, susceptible plants could be mistakenly selected as resistant, substantially reducing the effectiveness of breeding strategies,' Dr Simon explains.

This work was carried out in parallel with research examining the genetics of the plants, and screening of a global collection of over 100 basils. While Dr Simon, Dr Wyenandt and their PhD student Robert Pyne were conducting this genetic analysis and screening, another breakthrough occurred. The team's reliable, fast screening method culminated in the identification of a resistant exotic variety from Zanzibar called 'Mrihani'. Their results showed that this strange exotic basil, assumed to be of another species, actually turned out to be a variety of *Ocimum basilicum*, indicating that it could be a great candidate for traditional breeding.

Dr Simon and his team were surprised, as Mrihani neither looks nor tastes like sweet basil. With highly serrated leaves and a distinct liquorice flavour, Mrihani is not even close to being considered a sweet basil. However, as it is the same species as sweet basils, the team found that it readily reproduces with other sweet basil varieties to produce viable offspring. Thus, Mrihani was identified as a potential parent that could help the researchers develop BDM-resistant sweet basil varieties with a commercially acceptable flavour profile.

Characterising Resistance Inheritance

Over a period of two years, Dr Simon and his team crossed Mrihani plants with plants of another sweet basil variety, Rutgers University's breeding line 'SB22', which had shown high susceptibility to BDM but resistance to fusarium wilt – a fungal disease that can negatively impact growers. The concept was to develop plants with high resistance to both BDM and fusarium wilt at the same time.

BDM resistance in *Brassica* – the family including broccoli, cabbage and turnips – had previously been attributed to a single gene, but it was still unknown whether the inheritance of BDM resistance in sweet basils would follow a similar pattern. Where multiple genes determine disease resistance, developing disease-resistant varieties becomes more complicated.

The team's breakthrough of identifying a BDM-resistant variety of sweet basil was only the beginning. With repeated crossings over six successive generations, they tested the gene action and inheritance of BDM resistance. The researchers discovered that resistance is controlled by dominant genes – meaning that plants with one non-resistant gene and one resistant gene would still exhibit BDM resistance. However, this is complicated by resistance being influenced by two

Parent plants of the team's fusarium wilt-resistant and BDM-resistant sweet basil: SB22 sweet basil on the left (resistant to fusarium wilt) and Mrihani (BDM-resistant) on the right.

One of the team's basil varieties (Rutgers Obsession DMR, left) compared to a leading commercial sweet basil (right). BDM symptoms are visible in the commercial plants, while Rutgers Obsession DMR is disease-free.

separate and interacting gene pairs. Plants with one copy of a resistant gene at each of the two gene sites exhibited resistance, but plants with two copies of the non-resistant gene at either of the gene sites exhibited reduced overall resistance to BDM.

Dr Simon notes that this does not indicate that breeding reliably resistant sweet basil varieties is impossible, but rather that meticulous efforts are required to eliminate non-resistant genes and thus 'fix' the resistant trait in the plant. He suggests that simultaneously selectively breeding for desirable appearance and flavour traits will yield commercially acceptable sweet basil cultivars with BDM resistance.

The ability of basil breeders and researchers to respond rapidly to the emerging threat of BDM was significantly hindered by the lack of information about the genome structure and genetic diversity of sweet basils. Without this information, breeding efforts are more difficult and less effective. Understanding the genome of a species accelerates the development of new varieties as well as the utilisation of new gene-editing technologies.

To enhance the breeding of their BDM-resistant lineages of sweet basil and to facilitate efficient responses to future diseases, Dr Simon and his team took advantage of newer, more cost-effective genetic methods. They produced a genetic 'map' for sweet basil, which confirmed their results on BDM resistance inheritance from their earlier breeding studies. They also observed a high level of genetic diversity amongst sweet basil varieties, which accounts for their wide range of flavours and appearances. This work was spearheaded by Robert Pyne who conducted this basic research as part of his dissertation studies.

Towards Full BDM Control

Back in 2011, the Rutgers researchers and their collaborators at Cornell University, the University of Massachusetts and the University of Florida began intensive efforts to provide a solution to BDM in sweet basil. Building on Dr Simon's previous work on Mrihani and SB22, the team's breeding program faced significant challenges in producing a BDM-resistant variety with a flavour and appearance suitable for commercialisation. However, Dr Simon's extensive experience in developing new basil cultivars with unique aroma profiles provided a solid foundation for success.

In eight years, the breeding program produced and created 12 new sweet basil cultivars with BDM resistance. Of these, four have been commercialised by VDF Speciality Seeds, and provide growers with a substantial increase in BDM resistance. 'These new BDM-resistant sweet basils offer high yielding varieties, even when BDM is present, and protect growers from the threat of complete crop loss under high disease pressure,' says Dr Simon. Importantly, consumer taste tests of their new varieties have proven successful.

Dr Simon notes, however, that resistance is not equivalent to immunity. At high levels of disease pressure, BDM-resistant varieties can still exhibit symptoms. Commercial use of BDM-resistant basil varieties still requires growers to adhere to best management practices including the application of fungicides, but at a much lower rate. Growers who switched to BDM-resistant cultivars have been able to harvest later into the season than was previously possible, enhancing their yields and improving cost-effectiveness. Organic growers are reporting that they are now able to grow basil at long last without BDM issues.

Embracing Creativity and Diversity

Dr Simon believes that his team's success was due in large part to their creativity and diversity – combining expertise from many scientific disciplines with the shared vision of finding a solution to the devastation caused by BDM. The team included lab scientists, farmers, growers, distributors, food processors and PhD students who were all dedicated, creative problem solvers. While their battle has been won, their war against BDM continues. Only this time, the team is better armed.

Meet the researcher

Dr James E. Simon
School of Environmental and Biological Sciences (SEBS)
Department of Plant Biology
Rutgers University
New Brunswick, NJ
USA

Dr James Simon, Distinguished Professor in Plant Biology at Rutgers University, achieved his PhD in Environmental Stress Physiology from the University of Massachusetts, before continuing his research career at Purdue University for 17 years and Rutgers University, where he has now worked for 20 years. He is the Director of the New Use Agriculture and Natural Plant Products Program (NUANPP) and Director of the Rutgers Center for Agricultural Food Ecosystems (RUCAFE). Aside from breeding basil, catnip, oregano and African Indigenous Vegetables, Dr Simon has long focused on establishing sustainable food systems domestically and internationally, and has developed a holistic, culturally grounded, market-first, science-based model for tackling food system challenges that has been applied in several countries with a core focus in sub-Saharan Africa. Dr Simon's specific research interests include genetic evaluation of plant cultivars, selective breeding for health and nutritional value, plant chemistry, and the development of new crops. He has published over 350 scientific papers in numerous esteemed peer-reviewed journals and he has received multiple academic, industry, government and scientific awards for his work. In addition to his research, Dr Simon also develops and teaches undergraduate courses in EthnoBotany, Medicinal Plants, and Hemp and Medical Cannabis, directs the Rutgers Natural Plant Products Lab, supervises graduate students, and establishes partnerships between universities with the public and private sector.

CONTACT

W: https://breeding.rutgers.edu/basil-variety/
W: http://newuseag.rutgers.edu
W: https://ifnh.rutgers.edu/centers/food-systems-sustainability/
E: jimsimon@rutgers.edu

KEY COLLABORATORS IN BASIL RESEARCH

Dr Andy Wyenandt, Rutgers University
Dr Robert Pyne, VDF Speciality Seeds
Dr Joshua Honig, Rutgers University
Dr Beverly Tepper, Rutgers University
Dr Qingli Wu, Rutgers University
Dr Rodolfo Juliani, Rutgers University
Dr Ramu Govindasamy, Rutgers University
Dr Rong Di, Rutgers University
Dr Michael Lawton, Rutgers University
Dr Richard Raid, University of Florida
Dr Meg T. McGrath, Cornell University
Dr Li-Jun Ma, UMass
Dr Robert Wick, UMass
Dr Yigal Cohen and Yariv Ben-Nam, Bar Ilan University, Israel
Dr Nativ Dudai and Itay Gonda, Agricultural Research Organization, Israel

ACKNOWLEDGEMENTS

Dr Simon wants to recognise Dr Wyenandt, New Jersey's vegetable plant pathologist, for his expertise in disease management, as well as PhD student, Robert Pyne, who together conducted ground-breaking research in this project. Robert is now a basil breeder with VDF Specialty Seeds and the three are co-inventors of the first series of basil DMR plants: Rutgers Obsession DMR, Rutgers Devotion DMR, Rutgers Passion DMR and Rutgers Thunderstruck DMR. He also wishes to acknowledge Robert Mattera and Lara Brindisi, newer PhD graduate students in plant breeding that are now working to elucidate the sweet basil genome and breeding DMR into Thai and other ornamental basils. Dr Simon would like to recognise Rick Raid and Ann Hartmann at UF; Robert Wick, Li-Jun Ma, Anne Gershenson and Kelly Allen at UMass; and Meg McGrath at Cornell. He also wishes to thank Van Drunen Farms; VDF Specialty Seeds; Johnny's Seeds; KBC Industries; Dalponte Farms; Vinnini Farms in southern Jersey; C&B Farms and Alderman's in southern Florida; Shenandoah Farms; and so many more, along with the continued strong support and funding from the USDA and the US-Israeli BARD, which provided the resources for developing the downy mildew genetic resistance and control strategies.

FUNDING

United States Department of Agriculture (USDA) – Special Crops Research Initiative
USDA – National Institute of Food and Agriculture
The New Jersey Agricultural Experiment Station
Binational Agricultural Research and Development (BARD)

RUTGERS

NEW SORGHUM REFERENCE GENOME HIGHLIGHTS GENETICS UNDERLYING SWEET VARIETIES

Sorghum is a staple crop in many regions of the world. As such, this versatile plant has been selectively bred into a number of cultivars, including sweet varieties predominantly used for forage, silage, sweet syrup and bioenergy production. **Dr Elizabeth A. Cooper** and her team at the University of North Carolina at Charlotte generated a full reference genome for the sweet sorghum cultivar 'Rio' with the aim of understanding the genetics underlying the differences between grain and sweet cultivars. Their research could provide a vital tool for biologists and breeders to improve sweet sorghum lineages.

Crop Diversification Through Selective Breeding

The process of crop domestication generally consists of two stages. Initially, a wild plant is cultivated by humans for food or other purposes. Subsequently, these domesticated plants are 'selectively bred' by crossing plants exhibiting desirable characteristics, such as fast growth, disease resistance, and higher productivity. This 'diversification process' – when one population differentiates into two or more – produces separate plant cultivars which are specialised for particular purposes.

The cereal crop plant *Sorghum bicolor*, often known simply as sorghum, is an excellent example of this process. Through selective breeding, numerous sorghum cultivars have been produced, including sweet varieties that accumulate sugars in the leaves and stems of the plants at much higher levels than traditional grain sorghum cultivars. The drastic differences in the sweet cultivar 'phenotype', that is, the set of characteristics they exhibit, are produced by differences in the genes of these plant lineages that arose as they were selectively bred. However, the genetic mechanisms behind the sweet sorghum cultivars' sugar production and storage are still poorly understood.

In collaboration with the USA Department of Energy's Joint Genome Institute and other researchers from Clemson University in South Carolina, USA, Dr Elizabeth A. Cooper and her team at the University of North Carolina at Charlotte, USA have used advanced genetic sequencing techniques to generate a full reference 'genome', the sequence of all the DNA building blocks that comprise the genes for the sweet sorghum cultivar 'Rio'. Through examination of the Rio genome and comparison with a common grain sorghum genome, they aim to investigate the genetic mechanisms behind sweet phenotypes in sorghum. Their work highlights the genes that could be used as targets for further improvements to the lineage by

breeders and biologists. Additionally, their work provides an insight into how evolution and selection shape the genome.

Genetic Differences Between Rio and BTx623

The reference genome for sorghum that was available previously is for the short-statured, early maturing, grain sorghum cultivar 'BTx623'. The phenotype of this sorghum variety is very distinct from Rio and other sweet sorghum cultivars typically grown for their sugar content and high yields, and thus, provides a valuable comparison for exploring the genetic basis for these differences.

Among the whole-gene differences between the two varieties, 54 genes

appear to be unique to Rio, and 276 genes were present in BTx623 but absent from Rio. The majority of the differences between the sorghum varieties occur in genes belonging to large gene families that have been extensively expanded in grasses, including groups of genes involved in disease resistance, vegetative growth and plant stature, and stress responses. Dr Cooper and her team suggest that many of the differences between Rio and BTx623 reflect adaptations to local disease pressures. Other gene families present in BTx623 but not in Rio have a diverse array of functions within plants, and as such, may reflect any number of functional differences in the cultivars.

However, the number of whole-gene differences between the two lineages is relatively small, in comparison to the genetic diversity present in lineages of other crops, such as maize and rice. Dr Cooper and her team found that although the structure and content of the genomes are largely the same for both varieties, there are over two million small differences within the DNA sequence itself that affect the type and structure of the functional proteins produced within the plants' cells. These proteins have a diverse array of functions within the plants, such as transporting sugars between different regions of the plant.

Genetic Basis for Sweet Cultivars

Of the genes involved in sugar metabolism in sorghum, a small number of changes present in Rio involve sugar transport proteins. These transporters, which recently diversified in grasses, facilitate the movement of sugars between plant tissues, for example from the leaf in which the sugar is produced into the 'phloem' – the sugar-rich liquid transported around the plant in a system of vessels, comparable to the blood vessels in animals. Dr Cooper and her team discovered three sugar transporters are entirely absent in the Rio cultivar.

However, it is not yet clear how the loss of these sugar transporters affects sugar accumulation within the plants, because the specific function of the individual genes within the gene family are varied and not fully understood. 'The fact that several of these transporters have been deleted in Rio could be indicative of a mechanism for retaining sugar in the stalk, rather than moving it into the seed as the final storage sink,' suggests Dr Cooper. The genes responsible for these sugar transporters are 'expressed' – or turned on or off – at different times and locations within the developing sorghum plant.

Of the three transporter genes absent in Rio, one does not appear to be expressed at all in BTx623. This suggests that this is not a functional gene copy in sorghum and its deletion in Rio would have little to no effect. In contrast, another of the absent trio of genes is expressed in BTx623, particularly in the upper leaves and stalks during the flowering period. Dr Cooper and her team suggest that this indicates its absence in Rio may have significant effects on sugar metabolism.

Several other sugar transporters and sugar production proteins were produced in different quantities in the Rio and BTx623 cultivars, but these changes often did not correspond with any genetic differences between them. Dr Cooper suggests that instead, these

proteins must be regulated through other means within the plants, such as the presence or absence of sugar within the cells, or the activity of other genes and proteins within the process. 'These results highlight the complexity of the genetic interactions driving sugar accumulation in sorghum,' notes Dr Cooper.

Sugar Accumulation Patterns During Development

A key objective for Dr Cooper and her team, in addition to identifying the differences in the genome of sweet sorghum cultivars, was to disentangle the effects of plant maturation rate from those related to sugar accumulation. Sweet sorghum varieties typically mature later than grain sorghums, with sugar accumulation appearing to be tightly linked with flowering. To achieve this aim, the researchers chose a grain sorghum cultivar – 'PR22' – with a low sugar concentration contrasting with that of Rio, but with a similar maturation pattern. Dr Cooper and her team obtained samples of the plant tissues, including from the upper leaves and stems, throughout the development of the Rio and PR22 plants, to compare the process of sugar accumulation over time.

In both cultivars, sugar concentration increased linearly over time. However, the rate of increase was faster and the maximum sugar concentration reached was higher in Rio than in PR22. Sugar concentration increases significantly in Rio approximately a third of the way through their development, during the phase when the uppermost leaf – the 'flag leaf' – develops. However, it is notable that most of the genes of interest exhibited a delay in their expression in the Rio cultivar, suggesting that Rio increases the sugar content in its stems by not breaking down the sugars for use as energy during the onset of the flowering phase, but rather delays this process until after flowering. Several sugar transporters, however, exhibit the opposite pattern, which may indicate their role in moving sugars into the stem.

Genes related to other processes involved in sugar production, such as those that control complex carbohydrate metabolism, were found to be more active in the stems of Rio even when the copy of the underlying gene is identical in the two cultivars. This finding suggests that the activity of these genes is being regulated through other means, for example, by other genes involved in the pathway, by genetic differences at other locations in the genome, or by responding to the concentration of sugars in the plant cell. Dr Cooper explains, 'Rio begins to deposit sugar in the stems earlier in the growing season compared to the non-sweet sorghums, so it is inevitable that some changes in gene expression will begin to occur in processes that utilise sugars as their source.'

Some genes related to non-sugar transport proteins and other movement structures within the plant cells were expressed at higher levels in the stem and leaves of both cultivars. This suggests that these genes may also have important roles in the overall sugar accumulation process, even though they are not involved in sugar metabolism directly.

Building on the Foundation

Dr Cooper and her team's research provides a valuable insight into the complex genetic mechanisms underlying sugar production and accumulation in sorghum varieties. Even though the overall structure of the genome is similar between grain and sweet sorghum phenotypes, the key changes in genes regulating sugar processes, sugar transporters and sugar metabolism together play important roles in the accumulation of stem sugars. Their research findings and Rio reference genome will provide the foundation necessary for additional research aimed at improving sorghum cultivars further. Additionally, the sorghum cultivars examined by Dr Cooper and her team represent only a small proportion of the diversity present in sorghum lineages, and further opportunities exist to expand this research to incorporate additional cultivars.

Meet the researcher

Dr Elizabeth A. Cooper
Department of Bioinformatics and Genomics
University of North Carolina Charlotte
Charlotte, NC
USA

Dr Elizabeth A. Cooper earned her PhD in Molecular Biology at the University of Southern California, USA, before continuing onto postdoctoral research at the University of Miami, USA. She developed an interest in applying her expertise in evolutionary biology and genomics to agricultural systems during her subsequent positions at Clemson University, USA. She currently holds the position of Assistant Professor in Bioinformatics and Genomics at University of North Carolina Charlotte, USA, where her research team uses advanced technology to investigate the genetic basis of complex characteristics in a range of agricultural plants and other organisms. She is especially interested in examining the characteristics that lead to diversification amongst closely related groups. In addition to her research, Dr Cooper also devotes her time to teaching courses in genomics and evolution, and supervising the early-stage researchers in her laboratory.

CONTACT

W: https://elizcooperlab.com/
E: lizcooper@uncc.edu

KEY COLLABORATORS

Stephen Kresovich, Clemson University
Christopher Saski, Clemson University
Jeremy Schmutz, Hudson Alpha Institute

FUNDING

US DoE – Advanced Research Projects Agency (Energy)

FURTHER READING

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SUSTAINABLE WEED COEXISTENCE IN CORN CROPS

Agricultural weeds have the potential to cause significant crop loss. As such, conventional weed management practices have aimed to keep crop fields free from weeds through the broad application of herbicides. However, these practices have damaging consequences on the surrounding environment. Dr Rakesh Chandran and his team in the Agriculture and Natural Resources Department of West Virginia University have developed a more sustainable herbicide application regime that allows weeds to coexist with corn crops at acceptable levels, with the aim of improving environmental health without significantly sacrificing crop yield.

Defining 'Weeds'

What is a weed? Ask this question and you may get a variety of answers, depending on who you are speaking to. While many plants considered 'weeds' have similar characteristics, such as fast growth or high seed production, there is no single botanical classification for weeds. Instead, weeds are simply plants growing anywhere that they interfere with human activity, including gardens, lawns, and crop fields.

For farmers, weeds have the potential to significantly reduce crop yields by competing with cultivated plants for water, space, nutrients and light. Herbicide use to control weeds has helped agriculture to keep up with the food requirements of a growing human population, but this practice is under increasing scrutiny due to its undesirable side-effects. For instance, the widespread application of herbicides leads to vast swathes of land where the cultivated crop is the only plant species present. Such monoculture plantations contribute to the decline of beneficial animals and plants that provide valuable 'ecosystem services' – such as pollination, nutrient recycling, carbon storage, and pest insect control.

In the absence of other plants, soil left exposed immediately after crop harvest and before weed coverage is at risk of erosion and increased water and nutrient run-off into surrounding natural water systems. In addition, agricultural chemicals used for crop protection and plant nutrition frequently find their way into the surrounding environment, damaging or creating imbalances in fragile ecosystems and negatively impacting non-target plant and animal species.

Finally, the repeated application of herbicides has led to the emergence of herbicide resistance in many weed species, posing a significant risk to the continued efficacy of these conventional practices. While employing mixtures of multiple chemicals could further aggravate herbicide resistance, farmers in the state of Georgia have been able to manage resistant weeds through careful recruitment of Integrated Pest Management (IPM) practices. Indeed, IPM practices that balance the need for maintaining yields and reducing costs, while also preserving the natural environment are gaining popularity with farmers, governments and consumers.

Dr Rakesh Chandran and his colleagues at West Virginia University have been exploring alternative weed management techniques in corn cultivation, which are based on allowing acceptable levels of weeds to coexist with cultivated crops. The team aims to develop sustainable practices that maintain crop quality and yield, while being gentler on the surrounding ecosystems and alleviating the threat of herbicide resistance.

Conventional Weed Management in Corn

Cultivated corn, of the species *Zea mays*, is one of the most economically important crops across the world. It is an essential food staple in many areas, for both humans and livestock, and is used in the production of biofuels and other products. As such, vast areas of land are devoted to its production. 'In the USA alone, over 37 million hectares of land is dedicated to cultivating corn – an area larger than the UK and Ireland combined – amounting to billions of US dollars in annual revenue,' says Dr Chandran.

‘In the USA alone, over 37 million hectares of land is dedicated to cultivating corn – an area larger than the UK and Ireland combined.’

Dr Chandran discussing with Mr King, Dri-Lake Farms West Virginia, about the strategy of banding herbicides in cornfields and its potential benefits.

Weeds competing with young corn plants, especially in the first few weeks of growth, have the potential to cause significant losses in crop yield and quality. Conventionally, farmers have neutralised this threat by applying herbicides across entire corn fields to achieve complete weed control. With the advancement of agricultural machinery allowing farmers to cover large areas of fields in short periods, herbicides applied in this ‘broadcast’ fashion are a relatively cost-effective strategy to control weeds.

However, as discussed above, such broadcast application of herbicides is not the most sustainable or environmentally sound solution. Dr Chandran hypothesised that if left to grow in the space between rows of corn, wild plants – the ‘weeds’ – may not reduce corn yields significantly and could increase the floral biodiversity of cornfields, which in turn would provide valuable ecosystem services.

Banded Herbicide Application

Corn is typically grown in rows approximately 75 centimetres apart, leaving around 38 centimetres of unoccupied soil between the roots of plants from adjacent rows during the first growth phase. In fields where conventional broadcast herbicide application is used, this area is kept free from weeds. Dr Chandran’s team developed a ‘banded’ herbicide application technique, in which only the area directly around the young corn plants were treated, leaving untreated bands of freely growing weeds between the corn rows.

To determine the efficacy of this approach, Dr Chandran enlisted the help of corn growers in West Virginia, who were willing to provide the use of their commercial corn fields for extensive trials. ‘I carried out research over a period of five years to come up with data on corn yields as a result of applying a standard pre-mixture of herbicides, either as a conventional broadcast application or as banded application – where the herbicides were applied just over the corn rows so that weed germination to a distance of 19 centimetres on both sides is discouraged,’ he describes.

Banded herbicide application protects corn seedlings from the competing weeds during their vulnerable growth stage, while having positive effects on the overall biodiversity of the area. Dr Chandran and his team demonstrated that while fields treated with broadcast application of herbicides had biodiversity levels typical of monoculture crops, the fields treated with banded application had levels indicating ‘ecological diversity’ – meaning a high number of different species in a given area. Increasing plant biodiversity has positive consequences for other species too, such as beneficial predatory insects, and birds and mammals.

Importantly, the team’s banded herbicide treatment showed promise for maintaining similar crop yields to those achieved with broadcast herbicide application.

Overall yields were only about 8% lower (statistically insignificant) for fields treated with banded herbicide application in comparison to the broadcast application fields. However, such small losses in yields may be compensated for by the economic gains from lower herbicide usage combined with the valuable ecosystem services gained from a healthier environment.

Managing the Seed Bank

Sustainable weed control practices are gaining popularity with the public and farmers alike, but concerns over the long-term economic implications pose a major barrier to the widespread adoption of these methods.

A primary concern amongst corn growers was the potential for banded herbicide application to allow the build-up of the weed ‘seed bank’ – the number of seeds deposited into the soil. These seeds are capable of lying dormant for long periods and timing their development with the onset of favourable conditions. The sudden emergence of a large number of weeds from a stored seed bank during periods of favourable conditions may threaten to overwhelm cultivated plants and devastate entire crops.

With conventional broadcast herbicide application, weed species are fully controlled, and thus not given the opportunity to contribute to the seed bank. Dr Chandran suggests that banded herbicide application may be used in conjunction with other techniques, such as mechanical destruction of weed seeds at harvest, to counteract this problem. ‘Herbicides may be band-applied only when expected weed populations are below a certain threshold, and mechanical methods along with cultural methods, such as using cover crops, may have to be implemented to reduce the build-up of weed seed bank,’ he

‘1.3 million carbon footprints can be offset annually just by using banded herbicide application in corn cultivation in the USA.’

Relative sizes of corn cobs from the broadcast plot (left) and from the banded plot (right) that caused an overall yield reduction of 8% during 5-year research.

explains. ‘Cover crops manage biodiversity of agricultural fields, and weeds could be considered to be natural cover crops.’

Additional long-term investigations are necessary to determine the best solution for controlling the weed seed bank. ‘This is a valid concern since growers take pride in keeping fields weed-free, especially from resistant weeds such as *Amaranthus palmeri*, a single plant of which could produce over half-a-million seeds,’ continues Dr Chandran. ‘Growers have requested data from long-term studies under different weed population levels and weather conditions to gain confidence.’

Banded herbicide application may hold promise by encouraging a healthy dominance of wild-type weed species. However, Dr Chandran suspects it is unlikely that this practice would revert fields in regions that have become prone to resistant weeds as a result of herbicide overuse.

Towards Sustainable Weed Management

The risks of using alternative practices in farming may be balanced by the benefits gained from a healthier environment. Indirect benefits from improved ecosystem services can be difficult to quantify, but estimates can be achieved for some factors. For example, the carbon captured and stored from the atmosphere by plants can help to counteract our carbon footprint – the amount of carbon produced through heating our homes, travelling, or producing our food and goods.

The researchers calculated that allowing weeds to grow freely in even just a quarter of the 37 million corn hectares in the USA would produce a total weed biomass of 11 million tonnes, based on the projected 119.2 grams of dry weeds produced in each square metre. From this, they calculated the total carbon dioxide sequestered by the weeds by multiplying the total weed biomass by 0.5 (as carbon makes up half the weight of the dry weeds) and 3.67 (to convert to CO_2), to get 20 million tonnes.

‘As the carbon footprint of the average person in the USA is 15.5 tonnes, this means that 1.3 million carbon footprints can be offset annually just by using banded herbicide application in corn cultivation in the USA,’ says Dr Chandran. Thus, allowing weed species to coexist in agricultural systems may be a vital tool in the fight against climate change.

As these ecosystem services have benefits beyond the farm itself, Dr Chandran suggests that a cost-sharing program or increased farming subsidies may help to offset any losses experienced by farmers adopting more sustainable farming practices.

Conventional farming practices have focused on keeping production costs as low as possible and passing on these savings to consumers. This has resulted in relatively low-cost food options in many countries, but farming practices that sacrifice environmental health and long-term sustainability. Therefore, to future-proof our food production, the move towards sustainable farming may also require an increase in food prices. With food wastage estimated at around 40% in the USA, a greater emphasis also needs to be given to appreciating the value of food, especially food produced using more sustainable methods.

Dr Chandran’s promising research suggests that balancing affordability and sustainability is possible, but may require adjustments at every level from field to table to ensure its success. Dr Chandran and his colleagues aim to continue their investigation of alternative weed management practices and the associated ecosystem benefits. With additional work, the team hopes to improve the banded herbicide application technique further, and further quantify the benefits and costs associated with this method.

While one agricultural practice improvement alone is not enough to solve the climate crisis or halt environmental degradation, thousands of similar small adjustments in agriculture and other disciplines across the globe could cumulatively contribute to solving these problems.

Meet the researcher

Dr Rakesh S. Chandran
Agriculture and Natural Resources
West Virginia University
Morgantown, WV
USA

Dr Rakesh Chandran earned his PhD in Weed Science from Virginia Tech, USA, before continuing his post-doctoral research at the University of Florida. He currently holds the position of Extension Specialist and Professor of Weed Science at West Virginia University (WVU), in the Department of Agriculture and Natural Resources, WVU Extension Service, and Plant and Soil Science with the Davis College of Agriculture, Natural Resources, and Design. Dr Chandran carries out an applied research and extension program to assist growers with weed management in agronomic and horticultural crops in the region. He also devotes much of his time to teaching undergraduate courses in Weed Science and coordinating West Virginia University's Integrated Pest Management Program. Dr Chandran has authored numerous peer-reviewed publications, as well as book chapters, newsletters, fact-sheets and research reports. For his significant contributions to science, he has been the recipient of many awards and honours, including the 'Distinguished Service Award' from the National Association of Agricultural County Agents (NACAA) in 2016, and the 'Gamma Sigma Delta Extension Faculty Award of Merit' in 2018.

CONTACT

E: RSChandran@mail.wvu.edu
W: www.davis.wvu.edu/faculty-staff/directory/rakesh-chandran

KEY COLLABORATORS

Dr E. Scott Hagood (Jr), Professor Emeritus, Virginia Tech, Blacksburg, Virginia
Dr Wayne Currey, Principal Scientist, Weed Systems, Gainesville, Florida
Dr Carl Coburn, Former Undergraduate Student Intern
Mr Irwin King, Dri-Lake Farms, Charles Town, West Virginia
Mr Samuel Harper, Harper Farms, Moorefield, West Virginia
Mr Dan Foglesong, Foglesong Farms, Galispolis Ferry, West Virginia
Mr Rodney Wallbrown, Retd. County Agent, WVU Extension Service
Mr David Workman, Retd. County Agent, WVU Extension Service
Mr Craig Yohn, Retd. County Agent, WVU Extension Service

FUNDING

USDA – National Institute of Food and Agriculture
Crop Protection Chemicals donated by Syngenta Crop Protection and Bayer Crop Science

West Virginia University

THE BRITISH SOCIETY OF SOIL SCIENCE

Founded in 1947, the British Society of Soil Science (BSSS) is an international membership organisation and charity dedicated to the study of soil in its widest aspects. Funded through subscriptions and income from its publications, BSSS is a platform for exchanging ideas and representing the views of soil scientists to decision-making bodies. The Society stimulates research by hosting conferences and publishing two scientific journals, and promotes education through a number of initiatives in schools, colleges and universities. In this exclusive interview, we speak with **Professor Sacha Mooney**, President of BSSS, who describes the great importance of soil science research, and the varied ways that the Society advances this diverse and fascinating field.

To start, please explain why soils are fundamental to life on Earth.

Our soil is vital to our survival, primarily because it fulfils a wide range of important functions. At the top of the list is food production. We obtain more than 90% of our food from soil in some shape or form. A widely used quotation from Franklin Roosevelt captures the essence of this: 'A nation that destroys its soil destroys itself'.

However, soil does much more than provide us with our daily calorific intake. It filters our water, it regulates the Earth's temperature and thus impacts our climate, it is a home for millions of different organisms, it is the reservoir for the nutrients that plants require for growth; I could go on…

Why is soil science now more important than ever before? Are Earth's soils under threat?

Answering the second question first, yes, very much so, and as a result yes, soil science is indeed more important now than ever before. I would go as far as to say it is both the most important and, to an extent, the most exciting time ever to be a soil scientist.

Soil is at the heart of most of the global grand challenges and many of the UN Sustainable Development goals. The issues we face globally in mitigating and adapting to climate change are well documented, however the role of soil science in these is perhaps less so.

The management of soil impacts heavily on how much food we have available to eat, how clean the air is that we breathe and the quality of the water that we drink. Soils are under threat from several angles, not just our climate but in coping with large-scale agricultural intensification that has, and continues, to take place to deal with the rapid rise in global population.

The challenges facing farmers – the key people that manage our soils – are greater than ever before; we need more food, but with the use of less inputs either due to climate, finite resources or in attempts to behave in a more sustainable manner.

The challenges in responding to a changing climate from a soil perspective are significant to say the least. How do we manage our soils to prevent the devasting impacts of flooding? At the same time, how can we improve or at least maintain crop yields when there is less and less water available, or at least less water at the time it is most needed? These are some of the key questions we have to face globally and soil scientists are in the front line in this battle.

In what ways does the British Society of Soil Science support and advance soil science?

Our Society was established in 1947. Since then we have always been the place where those who have the passion, interest and excitement in understanding how the ground beneath our feet influences our daily lives, have come together. We have over 800 members from both the UK and overseas and our primary aims are around supporting the study of soil science, facilitating education and interactions between our members and supporting stakeholders and government in shaping new policy.

‘Soil does much more than provide us with our daily calorific intake. It filters our water, it regulates the Earth’s temperature and thus impacts our climate, it is a home for millions of different organisms, it is the reservoir for the nutrients that plants require for growth; I could go on.’

In 2010, we became an incorporated charity, merging with the Institute of Professional Soil Sciences. We have many members who are ‘practicing’ soil scientists, working in industry, and we take a lead in providing support and training for them. We also have a very strong early career membership and we support them by providing the opportunities for conferences, workshops and networking.

A particularly exciting and important part of our work in terms of how we promote and advance the understanding of soil science is that we publish – via Wiley – two long-standing and well-respected academic journals: the *European Journal of Soil Science* and *Soil Use and Management*. Our members get free access to these journals and they publish research from all around the world.

What types of research do your members conduct, particularly towards conserving and restoring the planet’s soils?

It is impossible to answer this question briefly, as soil science is a truly interdisciplinary subject, so the research is broad and wide. In addition, most of it is concerned with the sustainable management of soil, and where appropriate, remediation of degraded soils. As a discipline, many soil scientists would consider themselves to be soil physicists, chemists or biologists.

Myself, I am a soil physicist, and most of the research I conduct is focused on soil-water interactions and how the structure of a soil influences its behaviour – for example, how can we manage soils to make more water available to plants under times of drought, but also prevent them from flooding when the rainfall is high.

However, many soil scientists work across many scientific disciplines, and interactions with social scientists is becoming more commonplace. It is not uncommon for the modern-day soil scientist to have expertise in a wider range of areas, including spatial statistics, imaging and machine learning, metagenomics and modelling. It’s a diverse and exciting discipline.

Most of us are concerned with ensuring soils are able to fulfil the wide range of functions we need of them. In the past, soils have not been treated well and many are degraded. There are many examples of soils that are to an extent ‘broken’ in terms of compaction, pollution, erosion, low fertility, reducing organic matter and biodiversity. It is these themes that keep us awake at night and motivate us for research the following day.

‘I think a new way of working is emerging for many of us but my experience of the last few months has shown me that the passion for soils among soil scientists is something that is not easily dampened.’

What educational and outreach initiatives is the Society involved in?

The society has an Education Committee that is responsible for developing education and outreach activities to enable the delivery of parts of the Society’s Strategic Plan. Activities range from providing educational resources for teachers, to school visits, to supporting the procurement of equipment for young scientists in schools and colleges to undertake soil focused experiments. Many of these activities can be found on the soilnet website, which was developed with support from the society http://www.soil-net.com/.

We also keep an eye on the national education agenda and regularly feed into consultations about subject benchmarking statements to ensure the importance of soil science is recognised. This is important, as whilst soil is central to many current environmental issues, it not explicitly taught as part of the national curriculum in the UK.

We also host and support a wide variety of outreach events at both the national and regional scales. One of the most important for us is Open Farm Sunday organised by Linking Environment And Farming (LEAF), where farms open their doors to the general public once a year. This is an excellent opportunity for us to engage with the public in an environment where the significance of soil is very clear. Events such as this are very important to us as our aim is to secure the future of soils by promoting an enhanced understanding their critical importance.

We aim to make a positive difference to the sustainable management and long-term security of soils as this is critical to solving the environmental and societal challenges we face today. Outlining our enthusiasm for this to the scientific community, the relevant stakeholders and the wider public represents one of the most important things I think we can do.

In terms of preserving and restoring Earth’s soils, what types of agricultural practices does the Society advocate?

The choice of agricultural practice is primarily determined by a farmer and based upon many environmental factors including climate, soil type, cropping system along with other considerations such as history, experience, economics and the availability of equipment. Farmers receive advice on management systems from a wide variety of sources including government, advisors and other stakeholders. However, there is a controversial element of this as usually ‘one cap does not fit all’ and indeed a lot of the science concerning the ‘best’ practice for soil management is conflicting.

As a Society, we promote the concepts of soil health and quality, and the sustainable practices that can enhance these

such as retention of organic matter as a means of improving soil stability and soil health. However, as a Society we do not seek to promote specific agricultural practices over others as this risks alienating us from different soil interest groups; however, we do regularly engage with bodies that do advocate specific practices and foster discussion on both sides of the debate.

In 2022, the British Society of Soil Science will host the World Congress of Soil Science. Please tell us a bit more about this event.

The World Congress of Soil Science is a leading international soil science conference, held every four years in different countries and attended by over 3000 soil scientists from around the globe. It is a great honour that our Society has been tasked on behalf of the International Union of Soil Sciences to deliver the next one in 2022 in Glasgow – the last time it was held in the UK was in 1935!

The Congress theme, 'Soil Science – crossing boundaries, changing society', will focus on the link between soil and society, with sessions covering soil systems, soil processes, soil management and how we interact with and use soils around the world. There will be oral presentations, specialist workshops and discussion sessions across a wide range of soil disciplines. The core programme will be supported by tours and a cultural and arts programme for delegates and the wider public to explore our diverse environment and culture.

The Congress itself will take place at the world-class Scottish Event Campus, Glasgow from 31st of July until the 5th of August 2022, and we hope to welcome research scientists, policy makers, regulators, NGOs and anyone who has an interest in the sustainable use of soils, to discover the international state of the art in critical global issues and an opportunity to connect across all those who work with and rely on soils. Our planning for this has really ramped up in recent months and there is a real buzz in the Society about it at the moment.

Finally, how have the Society's activities been impacted by COVID-19, and how do you foresee this pandemic affecting the field of soil science in the UK and globally?

It has obviously been a very difficult time for everyone. The main impact on the Society has been the postponement, and some cancellation, of our meetings. As a Society we organise a wide range of specialist group meetings, workshops and training events, and the COVID-19 pandemic has meant that in the short term, these events have not been able to take place.

The UK is currently in lockdown, and as of today, we do not have a date for when that will change, so it has made planning very tricky. However, we are trying to be creative and looking for ways in which we can come together using digital environments.

Our Society Board and Council already take advantage of many digital communication platforms, so in many respects it has been business as usual; however, we have recently had to postpone our Annual Society meeting which was due to be held in Glasgow in September, and that is really disappointing. Assuming we will be unable to meet later in the year, we are now exploring how we might run a similar large event online. There will be challenges associated with this but advantages too, and in particular, I am hopeful we can take this opportunity to widen the participation and get as many members online at the same time as possible.

In terms of how the pandemic will impact on the field of soil science, I think we will probably fair better than other disciplines in terms of getting back on our feet quickly as research in soil science is often undertaken individually or in small groups. Once social distancing measures are introduced, it will most likely be possible for many of us to get back into the field and, to an extent, the laboratory to undertake research.

As for global communications, they have largely continued as normal, even increased in some cases, for example our journal editors have mentioned high numbers of research paper submissions with many scientists confined to their desks at home. I think a new way of working is emerging for many of us but my experience of the last few months has shown me that the passion for soils among soil scientists is something that is not easily dampened.

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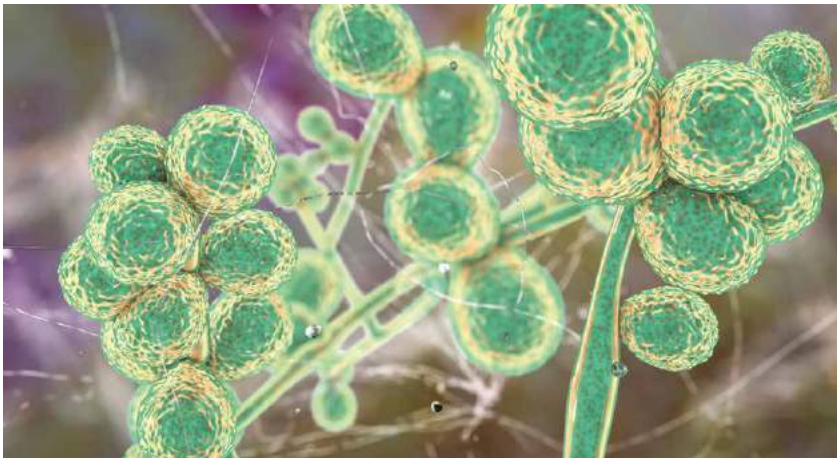
BRITISH SOCIETY OF SOIL SCIENCE

MICROBES: AGRICULTURE'S MICROSCOPIC HELPERS

Climate change and environmental degradation are increasingly threatening our ability to feed a burgeoning human population. Switching to agricultural practices that support beneficial soil microbes, and thus healthy soils, may help farmers achieve the yields required for continued food security. **Dr Zachary Senwo** from the College of Agriculture, Life and Natural Sciences at Alabama A&M University has spent over two decades exploring how agricultural management practices impact soil health. In an extensive new project, his team is investigating soil nitrogen cycling and the role of microbes in soil health.



Feeding a Growing Population

Many people across the globe struggle to feed themselves and their families. According to the United Nations World Food Program, 690 million people go to bed on an empty stomach each night. One in three people suffer with some form of malnutrition, including 150 million children worldwide. With the global human population predicted to reach 9 billion by 2050, crop yields will need to almost double to produce enough nutritious food to keep up with demand.

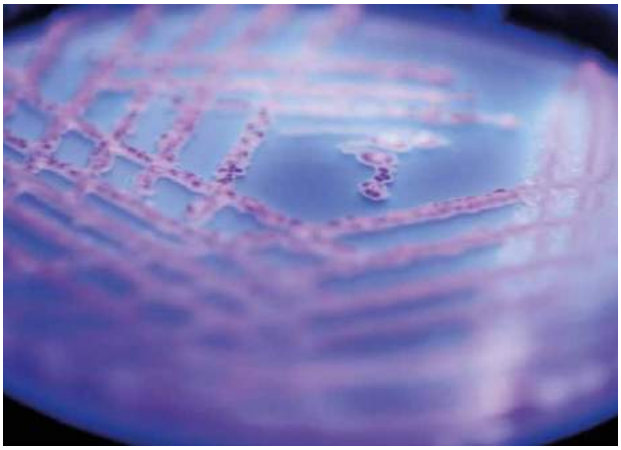
The intensive agricultural practices developed over the last few decades have helped us reach the high yields achieved today. However, these same practices have a myriad of negative consequences for the surrounding ecosystems. Chemical fertilisers leach into soils and waterways, disrupting the natural systems that help support productive farming. Pesticides affect beneficial insects as well as targeted pest species. Tillage, which involves turning the soil to reduce weeds, along with increased chemical inputs alter the natural soil communities that support good soil health and plant growth.

Unsustainable farming practices such as these ultimately lead to a breakdown in natural processes. Eventually, no matter how much extra fertiliser is added or how well pests are controlled, the same crop yields cannot be achieved, as evidenced by the incidence of 'yield gaps' – where farms fail to achieve the best observed yields for the region.

Working with Nature

To solve these problems, scientists and farmers are increasingly focused on developing strategies that work with, rather than against, the natural environment. The help we need may come in the smallest of packages. Soil microbes – the bacteria, fungi, and viruses that exist naturally in the soil – support plant health and growth through their important roles in nutrient cycling, breaking down organic matter, creating humus, soil structure, fixing nitrogen, promoting plant growth and development, and controlling pests and diseases. These vast and invisible microbial communities have evolved alongside plants for millennia, helping them to withstand harsh environmental conditions.

‘Organic growers will benefit tremendously from systems that integrate cultural, biological and mechanical practices promoting resource recycling, ecological balance and biodiversity conservation.’



Dr Zachary Senwo from Alabama A&M University has devoted more than two decades to researching soil microbiology and biochemistry. By examining the intricate relationships between plants and microbial communities, and how enzymes produced by microbes cycle nutrients in soils, he aims to contribute to the development of sustainable, effective agricultural management practices.

In his latest extensive research project, Dr Senwo and his team are examining nitrogen cycling in agricultural systems. As nitrogen is a key nutrient required for plant growth, and a main component in many chemical fertilisers, a better understanding of how to sustainably optimise the amount of usable nitrogen in soils will help to inform agricultural management strategies that improve both yields and environmental outcomes.

Promoting Nutrient Cycling with Microbes

Plant growth and development are typically limited by the amount of available nutrients, such as nitrogen, phosphorous, and sulphur. Although nitrogen exists in large quantities in the air, few plants can use it in this form. Instead, plants rely on mineral nitrogen from soils, in the form of ammonium or nitrate. However, much of the nitrogen contained in soils are derived from decaying plant and animal matter, and mainly ‘organic’ – or carbon-containing – amino acids and amino sugars. And this is where the soil microbial communities really shine.

Soil microbes produce a range of enzymes which help to turn organic nitrogen sources into plant-available mineral nitrogen through the process of mineralisation. By examining the activities of six soil enzymes involved in nitrogen cycling and four involved in carbon cycling, Dr Senwo demonstrated how the activities of certain enzymes can be reliable indicators of the amount of nitrogen mineralisation in soils. Thus, the activities of these enzymes could provide crop growers with valuable early feedback on how soil management practices, such as adding inorganic or organic materials to alter soil pH, are affecting soil health.

Promoting natural nitrogen mineralisation by adopting practices that support soil microbial communities could enable crop producers to maintain yields while also reducing the input of chemical fertilisers. Many crop farmers, particularly organic farmers, have already moved to more sustainable and environmentally friendly soil fertilisation options. Poultry litter – a mix of manure, spilled feed and bedding, and feathers from domestic fowl – provides an inexpensive and efficient additive to increase soil nutrients. However, concerns exist that even the addition of natural fertilisers like these could contribute to nutrient leaching if over-applied.

In his research, Dr Senwo discovered that phosphorous and nitrogen from poultry litter accumulates in soils. However, repeated applications of poultry litter accelerated the transformation of amino compounds into usable nitrogen sources. ‘The accumulation of organic and inorganic nutrients in soils stimulates microbial growth and activities and therefore, enzyme synthesis,’ explains Dr Senwo. This suggests that evaluating the long-term impacts of using poultry litter as an organic fertiliser requires predictions based on cumulative amounts added, rather than annual input rate or years of application.

Agricultural systems already affected by intensive management practices may require additional measures to restore proper function. Commercially available enzymes could help to restore nutrient balance and prevent further leaching in over-fertilised soils. However, as with other enzymes, their activities are sensitive to other conditions, such as temperature, pH, and the presence of metal compounds.

Dr Senwo and his colleagues examined the activities of three nitrate-reducing enzymes, obtained from a plant, a fungus, and a bacterium, in the presence of a range of different metals.

Because metal compounds are a natural component of soils, a better understanding of enzyme – metal interactions could help to inform strategies to reduce excess nitrates on farmlands.

Sustainable Improvement of Nitrogen Cycling

For his current research project on nitrogen cycling in agricultural soils, Dr Senwo has teamed up with scientists from organisations across the USA. 'This project enables strengthening integrative, multidisciplinary research for improved understanding of nitrogen cycling in agricultural soils, integrating biochemical and molecular techniques to detect microbes, delineate, predict and manage soil nitrogen in agricultural soils, and increasing the number of trained professionals, especially African-Americans, engaged in research, teaching and management of renewable resources,' says Dr Senwo.

The team is examining soil nitrogen cycling with relation to nitrogen compositions – or the relative amounts of organic and inorganic nitrogen in agricultural soils, the mineralisation and other transformation processes that increase the amount of plant-available nitrogen, plant uptake of nitrogen, and the production of enzymes related to nitrogen cycles in organic fertilisers and soils. 'Nutrient cycles are excellent models to test agricultural sustainability, being an inherent component for production and economic success,' says Dr Senwo.

In addition to their thorough research objectives, Dr Senwo and his team are providing research support to small-scale organic farmers. Although organic farming is gaining traction, farmers have indicated a general lack of knowledge in organic production techniques. Even the common methods used to assess soil nitrogen levels have been based primarily on conventional fertilisers, limiting their efficacy in farming systems relying on organic nitrogen sources and natural mineralisation processes. More sophisticated tools are desperately needed to assess nitrogen availability and improve nitrogen uptake by crops on organic farms.

'Agricultural producers cannot be competitive if they do not have access to research data backed by a strong extension support,' says Dr Senwo. 'Organic growers will benefit tremendously from systems that integrate cultural, biological and mechanical practices promoting resource recycling, ecological balance and biodiversity conservation.'

To achieve their research objectives, Dr Senwo and his team are collecting samples from agricultural fields using a range of management practices, including both conventional and organic farms. They have also included tropical agricultural ecosystems by forging connections with growers from overseas. Because environmental conditions affect the compositions and functions of microbial communities, a better understanding of how these processes work in diverse ecosystems across the world will help improve food security beyond the USA.

A key aim of Alabama A&M University is to contribute to solving environmental and agricultural issues by producing well-trained and qualified graduates. Dr Senwo's research project builds on an excellent educational framework by providing further opportunities for undergraduate and graduate students to gain valuable experience while contributing to real-world research. The experience that the students gain in soil microbiology and molecular techniques will equip them for future research in microbial ecology.

Dr Senwo and his team envision this project will facilitate an upgrade to the soil and environmental sciences programs at Alabama A&M University, and many aspects of the project may contribute to other research programs within the university. The team plans to evaluate the project progress each year, offering ideas for improvements for subsequent years.

'Furthermore, we intend to use our results acquired with the study as a springboard for future studies investigating additional or alternative agricultural management practices which will provide economic, social and environmental sustainability,' says Dr Senwo. With climate change and other environmental problems making it increasingly difficult for farmers to meet food demands, thorough and reliable research to inform sustainable agricultural practices may be our only hope for ensuring food security for generations to come.

Meet the researcher

Dr Zachary N. Senwo
Department of Biological & Environmental Sciences
College of Agricultural, Life and Natural Sciences
Alabama Agricultural and Mechanical (A&M) University
Normal, AL
USA

Dr Zachary N. Senwo received his BSc from University of Georgia, MSc from Alabama A&M University and PhD in Soil Microbial Biochemistry and Chemistry from Iowa State University, focusing on biochemistry and chemistry of nitrogen cycles in agricultural and metals-enriched soils. He also received a Certificate in Global Health from the Sparkman Center for Global Health at the University of Alabama, Birmingham. Dr Senwo currently holds the position of Professor in the College of Agricultural, Life and Natural Sciences at Alabama A&M University. His main research areas include enzymatic and microbial processes in soils; exploring and developing novel methods for soil enzymes catalysis; soil microbial communities' response to varying land disturbances and climatic changes; metal/non-metal inhibition of enzymes; chemical partitioning and bioreduction of soil metals; and harnessing fungi's enzymatic potentials in bioenergy and bio-based fuel research. He has published over 150 research articles in peer-reviewed journals, and has been invited to present his work and host workshops at over 80 academic events across the world. Dr Senwo also devotes time to teaching a range of undergraduate and graduate courses and supervising graduate students. In 2019, he was a Fulbright Scholar to Kenya on tropical agroecology and sustainability. Additionally, Dr Senwo successfully developed and launched study abroad research and academic programs with institutions in countries across the globe.

CONTACT

E: zachary.senwo@aamu.edu
W: https://www.agrilinks.org/users/znsenwo

KEY COLLABORATORS

Dr Terrence Gardner, Soil and Environmental Microbial Ecology, North Carolina State University, Raleigh, North Carolina
Dr Zhongqi He, USDA-ARS Southern Regional Research Center, Commodity Utilization Unit, New Orleans, Louisiana
Dr Verónica Acosta-Martínez, USDA-ARS, Cropping System, Wind Erosion and Water Conservation Research Unit, Lubbock, Texas
Dr Priscilla Mfombep, HTTTC-Kumba, University of Buea, Cameroon

FUNDING

USDA – National Institute of Food and Agriculture

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ALABAMA A&M UNIVERSITY

CATALYSING AGRICULTURE WITH ENZYMES

Enzymes make life as we know it possible. These active proteins are vital in nutrient cycling, metabolism, and cell functioning. With their diverse range of functions and ubiquity, enzymes could offer techniques to support healthy agricultural ecosystems, and as such, improve sustainability and future food security. Understanding their activities is vital to the organic agriculture revolution. **Dr Zachary Senwo** and his team at Alabama Agricultural and Mechanical (A&M) University have contributed years of important research to uncover the potential of enzymes towards informing novel agricultural practices.

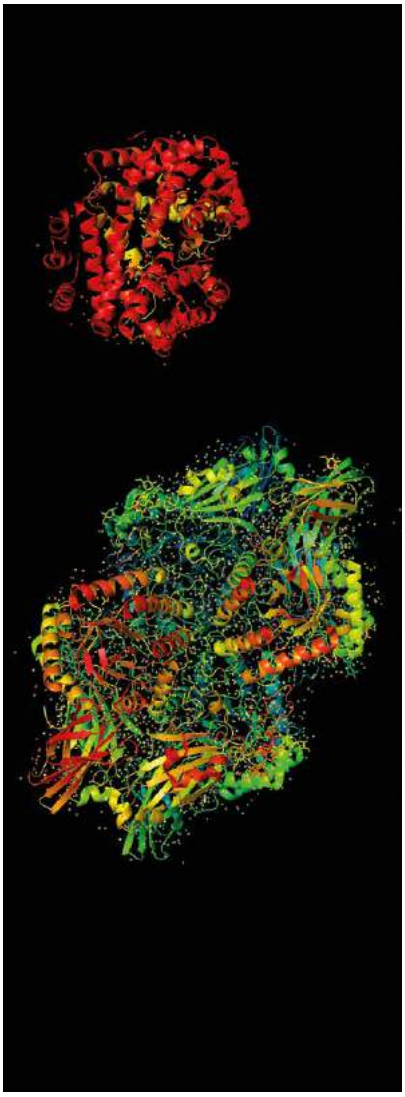
Nature's Tiny Machines

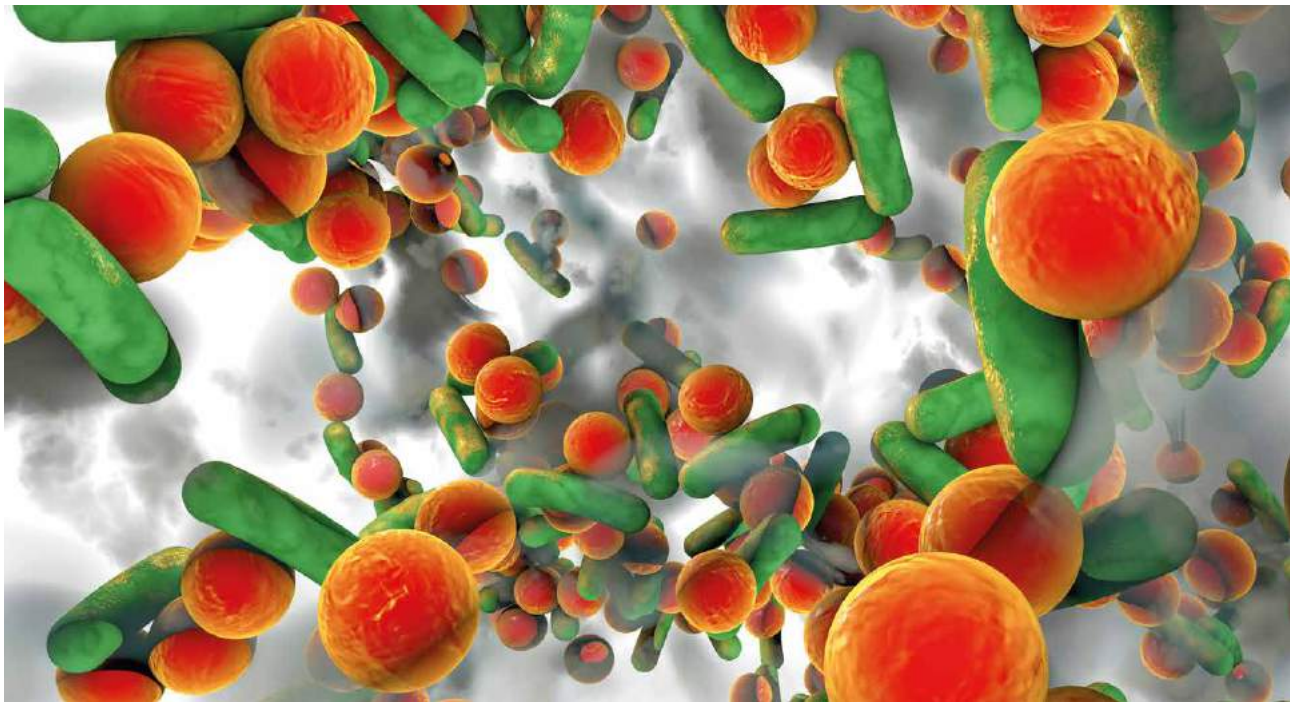
We are probably all familiar with enzymes from our school textbooks – the hard-working proteins that have fundamental roles in numerous biochemical functions, such as digestion and cell signalling. Enzymes 'catalyse' – or speed up – biochemical reactions that would otherwise occur millions of times slower. Without them, life on Earth would be impossible.

These tiny biochemical machines are predominantly involved in breaking down or building molecules. Some enzymes help to break down complex carbohydrates into simple sugars such as glucose, which is an important source of energy for microbes, plant, and animal cells. Others cleave mineral compounds into smaller molecules that have much increased bioavailability. With potentially hundreds of thousands of individual enzymes catalysing over 5000 different biochemical reactions, enzymes present vast, untapped potentials for solving some of our most pressing environmental and agricultural issues.

Intensive agricultural practices have wrought immense damages on the environment, the effects of which are becoming harder to ignore. Chemical fertilisers and pesticides leach from soils to disrupt aquatic ecosystems and destroy beneficial communities of soil microbes that maintain soil quality and health. A damaged ecosystem can no longer provide such important ecosystem services, as drought resilience, clean water, photosynthesis, air purification, and natural or biological pest control. Farmers are struggling to maintain high quality and high yields with the growing pressures from climate change, emerging plant diseases, and soil degradation. Without a revolutionary change in agricultural practices, the future food security of our growing human population will be severely at risk.

Working *with* the surrounding ecosystem instead of *against* it could help restore environmental health while ensuring that food demands are met. Enzymes – produced by soil microbes and plants, and through commercially available soil additives – could be a key tool in this endeavour. However, there is





still much to learn about enzymes and their actions. Before farmers can adopt new practices that take advantage of the power of enzymes, they need reliable information based on robust evidence.

Dr Zachary Senwo and his team of researchers from the Department of Biological and Environmental Sciences at Alabama A&M University have devoted years of research to uncovering some of the mysteries of enzymes. Their important work investigating the mechanisms, activities, specificities, and potential applications of enzymes could help to inform new agricultural practices that not only maintain, but also restore the health of agricultural ecosystems.

Investigating Enzyme Activities

Investigating the activities of enzymes is a complex process. Experiments typically measure the amount of 'substrate' – the compound that the enzyme acts upon – converted to the product for a set time and amount of enzyme. However, this is just the first of many factors that scientists must consider when investigating enzyme activities, especially in soils.

Enzymes, being proteins, are sensitive to their surrounding environment. If temperatures are too low, their activities slow and eventually halt completely. If the temperature is too high, their structures quickly unravel, rendering them useless. Similarly, enzymes have functional ranges for other conditions, such as pH, outside of which they cease to function. The presence of some minerals and inhibitory molecules can also affect their efficiencies. To fully understand the potentials of various enzymes, scientists must first examine how the enzymes function under various conditions.

A better understanding of the optimal conditions for individual enzymes could aid especially limited resource farmers or agricultural producers wanting to use them for improving soil health and plant productivity. For example, enzymes functioning optimally in alkaline conditions would make a poor choice as an additive for acidic soils, and vice versa. Additionally, farmers wanting to promote the activities of enzymes produced by soil microbes may be able to tune their soils to achieve optimal conditions by using natural soil amendments.

In addition to investigating individual enzymes important in soil nutrient cycling and transformations, Dr Senwo and his team have also been developing protocols for measuring activities of different types of enzymes in organic and conventional agricultural systems. One such development was for the enzyme maltase, which is important for the conversion of the complex sugar maltose into the simple sugar glucose, so that it can be used as a source of energy by beneficial soil microbes.

Previous testing protocols had relied upon the use of artificial substrates, and as such had limited use in agricultural systems. 'With the promotion of organic and sustainable agriculture systems and the use of poultry litter as soil amendments, which results in the addition of maltose into the soil system, it is worth developing alternative assay protocols for determining maltase activity using a natural substrate – maltose and measurement of its natural product – glucose,' says Dr Senwo.

Supporting Sustainable Agriculture

Plants have an abundance of carbon available to them, as they sequester it from carbon dioxide in the atmosphere, but other substances are more difficult for them to obtain. For example, the availability of nitrogen and phosphorous is often a limiting

factor for plant productivity because, unlike carbon, most plants cannot create their own usable forms of these nutrients. Instead, plants rely on soil microbes to produce the enzymes that break down larger compounds into usable forms, which they can then absorb through their roots.

Numerous enzymes replenish important plant nutrients, many of which are still poorly understood. Enzymes break down the proteins in decaying plant and animal matter, and through 'nitrogen mineralisation' and other associated processes produce the forms of nitrogen needed by plants for their growth and development. Similarly, enzymes help replenish the levels of other soil nutrients, such as phosphorous, sulphur, and potassium. For organic farmers eschewing the use of chemical fertilisers, a better understanding of the enzymatic processes involved in nutrient cycling and transformations is important for informing soil management decisions.

Dr Senwo and his team's research has included both commercially available and wild derived enzymes from a range of sources, including bacteria, fungi, and plants. Their work on Alabama's red clay soils demonstrated how soil conditions can influence the availability of phosphorous by enhancing or inhibiting the actions of enzymes involved in the cycling and transformations of this nutrient. Similarly, their work on the activities of sulphur-cycling enzymes provided additional insights into the value of investigating the actions of individual enzymes rather than only measuring total enzyme activities.

Developing reliable techniques for monitoring nutrient conversion rates in soils could also help farmers take actions to promote these processes before plant health suffers. Dr Senwo and his team investigated a range of enzymes involved with nitrogen mineralisation, demonstrating how their activities are impacted by factors such as the amount of substrate available, pH, temperature, soil moisture content, and the ratio of carbon and nitrogen in the soil. They showed how one of the enzymes investigated could be used as a reliable indicator of the level of nitrogen mineralisation occurring in the soil.

Through some of Dr Senwo's other research, he has demonstrated the importance of the soil microbial communities. These beneficial microbes help confer drought resilience to plants, improve nutrient availability through the enzymes they produce, and thus help farmers grow larger, healthier plants.

Soils already degraded over decades of intensive agriculture may need extra help to restore full functions. By exploring the activities of enzymes important to soil microbes, such as those converting complex sugars into glucose, Dr Senwo and his team have generated important information to support soil microbes. Farmers could use this information to provide optimal conditions for microbial enzyme activities by using soil amendments.

Environmental Clean-up Crew

Enzymes are not only a promising avenue for progress in agriculture directly – they may also be able to help reverse some of the environmental damages from agriculture and industry by cleaning up pollutants.

Excess nitrates leached from chemical fertilisers continue to pose a problem for ecosystem health. Denitrifying enzymes that help break down or biochemically reduce nitrates could be used to remove some of this pollutant from soils and waterways. Dr Senwo and his team assessed the activities of three denitrifying enzymes, obtained from a plant, a fungus, and a bacterium.

Although the plant enzyme had the highest activities, it was also more sensitive to the presence of metals – which are present in varying quantities in soils and water. In contrast, the bacterial enzyme had lower activity, but was more stable in the presence of higher concentrations of metals. The team's findings further illustrate that selecting the right enzyme depends on the environmental conditions as well as the efficiency of the enzyme.

Conclusion

Understanding the activities of enzymes, including which are the most efficient and the conditions promoting or inhibiting their actions, is a fundamental step towards developing agricultural and environmental techniques that harness their power. Along with other soil-friendly organic practices, promoting enzyme activities could help to support plant health and productivity through their role in nutrient cycling and transformations.

Dr Senwo's research is pertinent and timely – better agricultural and environmental practices are becoming increasingly urgent, but we need reliable evidence to inform these techniques. Research is providing the foundations upon which the agricultural revolution and environmental sustainability are being built. With sustainability and environmental health being its core ethos, this change is good for everyone.

Meet the researcher

Dr Zachary N. Senwo
College of Agricultural, Life and Natural Sciences
Alabama Agricultural and Mechanical (A&M) University
Normal, AL
USA

Dr Zachary N. Senwo holds the position of Professor in the College of Agricultural, Life and Natural Sciences at Alabama A&M University, where he pursues his research interests in soil microbial biochemistry, microbiology, chemistry, enzymology, environmental science, and toxicology. He earned his PhD in Soil Microbial Biochemistry and Chemistry from Iowa State University, in which he focused on the biochemistry and chemistry of nitrogen cycles in agricultural and metal-enriched soils. In addition to his research and teaching activities, Dr Senwo has served as an expert advisor for numerous projects across the globe, helping to improve agricultural systems, create sustainable agriculture and ecotourism business models, and reduce toxicity of important staple food crops. In 2019 he was awarded the Fulbright Fellowship to the University of Nairobi in Kenya, to develop and strengthen capacity building programs in Tropical agriculture and sustainability.

CONTACT

E: zachary.senwo@aamu.edu
W: https://www.agrilinks.org/users/znsenwo

KEY COLLABORATORS

Dr Terrence Gardner, Soil and Environmental Microbial Ecology, North Carolina State University, Raleigh, North Carolina
Dr Zhongqi He, USDA-ARS Southern Regional Research Center, Commodity Utilization Unit, New Orleans, Louisiana
Dr Verónica Acosta-Martínez, USDA-ARS, Cropping System, Wind Erosion and Water Conservation Research Unit, Lubbock, Texas
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FUNDING

National Institute of Food & Agriculture - United States Department of Agriculture

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ACKNOWLEDGEMENTS

This paper is a contribution from the Winfred Thomas Agricultural Research Station, Alabama A&M University and supported by USDA – National Institute of Food and Agriculture. Trade or manufacturers' names mentioned are for information purposes only and do not constitute endorsement, recommendation, or exclusion by either Alabama A&M University or USDA – National Institute of Food and Agriculture.

REGENERATIVE AGRICULTURE: PUTTING THE HEART AND SOUL BACK IN FARMING

Modern industrial agriculture has helped farmers meet rising food demands, but these practices are contributing to a range of environmental problems. Regenerative agriculture holds promising solutions that could help to restore and maintain healthy ecosystems and contribute to climate change mitigation, while keeping pace with food demands and enhancing farmers' resilience to environmental stressors. Through her research, **Dr Hannah Gosnell** aims to understand what motivates cattle and sheep farmers – also known as ranchers – to adopt and sustain the use of regenerative practices and what challenges must be navigated. Her work is informing efforts that encourage farmers to transition to these methods.

Why Regenerative Agriculture?

Developments in agricultural practices over the last few decades have allowed farmers to increase their yields significantly, helping production keep up with the rising food demands of a rapidly expanding population. However, a growing body of evidence has demonstrated how these modern techniques are also contributing to environmental degradation, biodiversity loss, soil depletion, and climate change.

Deteriorating environmental health, in turn, is having serious consequences for agriculture. For instance, droughts are increasing in incidence and severity because of climate change, while depleted or degraded soils have a reduced ability to confer drought resilience to crops. To maintain yields, farmers have had to increase the amount of chemical fertiliser they use. Many weeds and insects have developed resistance to pesticides, requiring higher application rates to achieve suitable levels of control. As such, farmers are having to do more and spend more to achieve the same level of productivity each year.

A growing number of farmers are reaching a breaking point. The time is ripe for a new kind of agriculture that offers alternatives to unsustainable farming practices.

Regenerative agriculture provides the solutions we need for our future food security. Consisting of a set of ideas and practices that aim to improve soil and ecosystem health, regenerative agriculture also contributes to the wellbeing of farmers and to their communities.

The suite of regenerative practices associated with cattle and sheep farming (called 'ranching' in the US) includes managing grazing to allow pastures to recover and reduce bare ground, capturing and storing carbon within the soil, reducing synthetic fertiliser application to restore soil health, and making decisions that account for the natural complexity of ecological systems, often through adoption of the systems thinking associated with 'holistic management'. These practices do not simply sustain food production methods that deplete resources, but actively aim to improve and regenerate the resources they use.

Regenerative practices help to restore resilience in agriculture by supporting functional ecosystem processes, thereby improving soil health and 'ecosystem services' – such as improved soil water retention, drought resistance, and natural pest control. Because regenerative agriculture focuses on whole system benefits, climate change mitigation and adaptation can be incidental to the larger enterprise and need not be the sole focus for transitioning from conventional approaches.

Additionally, regenerative practices provide a low-cost, low-tech approach to farming that replaces expensive chemical inputs and reduces labour, improving economic outcomes and reducing dependence on the agricultural chemical industry.

However, regenerative agriculture is challenging because it requires a deep understanding of ecological processes, along with the skills required to plan, monitor and move livestock more frequently to support cycles of grass regeneration, and to feed the soil microbial community. These barriers, as well as social and traditional norms, may discourage farmers from making the transition to regenerative agriculture. Understanding what motivates the farmers that have made the switch can help inform policies, incentives, outreach, and support mechanisms to encourage increased uptake of regenerative practices.

Dr Hannah Gosnell, a Professor of Geography in the College of Earth, Ocean, and Atmospheric Sciences at Oregon State University, has been investigating the human dimensions and social aspects of regenerative agriculture in her pioneering research projects. While previous research has considered the political and practical aspects of transitions to regenerative agriculture, her novel approach represents the first efforts to understand the personal factors involved.

'The overarching challenge is understanding what worldviews, values, beliefs, and other factors influence farmer and rancher decision-making, especially as it relates to transitioning to regenerative agriculture, and how policies, institutional arrangements, outreach and engagement can support the process,' Dr Gosnell explains.

Catalysing Transformative Change

Despite its many advantages, numerous challenges discourage farmers from adopting regenerative agriculture. For example, many lack information and experience about regenerative practices, having only been exposed to conventional methods. The cost of transitioning and the risks involved can seem insurmountable. Peer pressure, fear of stigma, and having to shift social groups can also prevent the necessary paradigm shift to higher-order systems thinking. Understanding and learning how to manage their agricultural systems regeneratively can take farmers years of dedicated effort.

Through extensive interviews with US ranchers and Australian farmers who have experienced success grazing their sheep and cattle using regenerative practices, Dr Gosnell discovered that for many early adopters of these practices, the catalyst for change came in the form of a crisis. 'For the majority of the farmers and ranchers interviewed, the trigger which opened their mind to the possibility of a different way of managing their property was some form of personal or business crisis, be it environmental, economic, health, or psychological,' says Dr Gosnell. 'The crises that the farmers experienced, often a series of events, led to feelings of desperation and vulnerability which forced them to reappraise themselves and their farming practices in a critical light.'

A growing realisation that their conventional farming practices were not adequately addressing repeated and persistent difficulties enabled the farmers to work through the obstacles involved with transitioning to regenerative agriculture. However, this realisation alone was not enough. It was not until an alternative vision of agriculture was presented to them that the transformation could begin. For many of the farmers interviewed, exposure to regenerative practices – for example during a public talk or during conversations with their peers – produced a moment of epiphany, prompting radical changes in thinking and behaviour.

Dr Gosnell discovered that for many of the farmers she interviewed, negative experiences with agricultural chemicals – such as rising costs and declining efficacy – was the crisis that compelled them to consider other methods of producing food and fibre. Conversely, learning about how organic fertilisers – such as compost – benefit soil microbes, and thereby contribute to improved

plant health, higher yields, and enhanced drought resilience, was exciting to farmers and allowed them to shift from thinking about soil as a 'chemical reservoir' to viewing it as a biological system in its own right.

Learning about ecosystem function and how regenerative practices can work with these natural processes allows farmers to 'see' the land differently. This demonstrates the important role that cognitive factors play in transformation. Dr Gosnell notes that this change in the way farmers view their land results in 'new mental models, attitudes, beliefs, and ultimately, behavioural change.' For most of them, switching to regenerative practices brought their farming into alignment with their personal ethics and values, offering them greater personal fulfilment. As one interviewed farmer said of conventional agriculture: 'That whole philosophy of trying to kill things that want to grow and trying to grow things that want to die, it's incredibly soul destroying and costly.'

Becoming more in touch with the life on their land can also positively affect farmers' emotions and sense of wellbeing, leading to self-amplifying positive feedbacks that help sustain behavioural changes. In other words, seeing positive results on the land associated with regenerative agriculture helps farmers feel happier, and so they want to keep doing it and learning more. This also illustrates how agricultural landscapes can be thought of as social-ecological systems, where positive results in social or ecological realms often lead to positive gains in the other.

Translating the Results into Motivators

Obstacles preventing farmers from transitioning to regenerative agriculture exist in political, practical, and personal spheres. Dr Gosnell's work demonstrates that measures to increase uptake of regenerative practices must address all three spheres to be successful.

Some efforts to scale up regenerative agriculture have focused on expanding markets for regeneratively raised products so as to provide consumers with the option to 'vote with their forks'. However, this strategy may not be as effective as some believe, since it does not address the challenges on the supply side. Because of the role that personal and social factors play in the decision to switch to regenerative agriculture, Dr Gosnell and her co-authors suggest that measures targeting the supply-side are necessary.

Financial incentives to adopt regenerative practices implemented by a growing number of governments – such as payments for carbon capture – offer a strategy that focuses on the supply-side. But although these are beneficial for easing the transition to sustainable practices, Dr Gosnell's work suggests that they do not provide enough motivation by themselves. Ranchers who generated carbon credits through the US Chicago Climate Exchange, for example, reported that the costs of transitioning – time, labour, and financial – far outweighed the payments they received for captured carbon. Their motivation for adopting regenerative agriculture, and therefore climate-smart practices, preceded and transcended the incentives provided.

Providing opportunities for farmers to experience alternative ways of producing food and fiber can help them to overcome barriers to transition, for example, increasing access to social and peer networks, microscope clubs to explore soil and soil microbes, and outreach and demonstrations. Dr Gosnell's findings demonstrate how educators, consultants, and mentors can facilitate 'induced epiphanies' by providing the alternative vision of agriculture to farmers unsatisfied with their current practices. She suggests that governments should develop and support programs that more effectively engage farmers in the personal sphere, such as peer-to-peer learning programmes. The opportunity to engage with like-minded peers while exploring regenerative agriculture facilitates the emergence and solidification of new farmer identities and promotes the development of new cultural norms.

Farmers transitioning to regenerative agriculture, and especially those that have been trained in holistic management and holistic decision-making, typically demonstrate a cognitive shift to systems thinking, a willingness to consider even radically alternative ways of thinking and practice, a willingness to learn, and enhanced knowledge and observation of ecosystem processes associated with soil and pasture health.

Dr Gosnell's extensive research provides convincing evidence that to promote the magnitude of change necessary for an agricultural revolution, we must remember that farmers are people – with their own thoughts, values, beliefs, and social environment. The right strategies and incentives are critical for promoting the widespread uptake and continued use of regenerative practices.

Our future environmental, economic, and societal well-being hinges on the decisions we make today. Since a vast proportion of available land globally is used for livestock production and growing crops, the positive impacts that a large-scale transition to regenerative agriculture could have for biodiversity, overall environmental health, and climate change mitigation could quite literally change the world.

Meet the researcher

Dr Hannah Gosnell
College of Earth, Ocean, and Atmospheric Sciences
Oregon State University
Corvallis, OR
USA

Dr Hannah Gosnell earned her PhD in the Department of Geography at the University of Colorado, Boulder, before continuing her research career at CU's Center of the American West. She currently holds the position of Professor of Geography in the College of Earth, Ocean, and Atmospheric Sciences at Oregon State University, and is also affiliated with the Australian Centre for Culture, Environment, Society and Space at the University of Wollongong, Australia; and the Centre for Sustainability at the University of Otago, New Zealand. Dr Gosnell's research interests include agricultural landscape change, water resource management, climate change and environmental governance in the context of rural working landscapes. She has also contributed her time and expertise in numerous roles at the American Association of Geographers, including being elected as Chair of the Human Dimensions of Global Change Specialty Group and the Rural Geography Specialty Group.

CONTACT

E: gosnellh@geo.oregonstate.edu
W: http://ceoas.oregonstate.edu/profile/gosnell/
W: http://blogs.oregonstate.edu/hannahgosnell/

KEY COLLABORATORS

Susan Charnley, Research Social Scientist, U.S. Forest Service Pacific Northwest Research Station, Portland, OR
Nicholas Gill, Associate Professor, School of Geography and Sustainable Communities, University of Wollongong, Australia
Bruce Goldstein, Associate Professor, Environmental Studies Program, University of Colorado, Boulder, CO
Kerry Grimm, Senior Lecturer, School of Earth and Sustainability, Northern Arizona University, Flagstaff, AZ
Julia Haggerty, Associate Professor of Geography, Montana State University, Bozeman, MT
Paige Stanley, PhD Candidate, Department of Environmental Science, Policy and Management, University of California, Berkeley, CA

FUNDING

US Forest Service, Pacific Northwest Research Station
US Department of Agriculture, Northwest Climate Hub
US National Science Foundation

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Oregon State University

REGENERATIVE AGRICULTURE

COVER CROPS

Plants that cover the soil between harvest to prevent soil erosion, and improve soil quality and biodiversity

INTEGRATING LIVESTOCK

Combining crops and animals in a circular ecosystem

NO-TILL SYSTEMS

Minimal soil disturbance reduces soil erosion and boosts biodiversity

MINIMISING CHEMICAL INPUTS

Little or no pesticide, herbicide and chemical fertiliser use, to increase ecological health

ROTATING CROPS

Crop rotation reduces the build-up of crop specific pest and diseases

INCREASING BIODIVERSITY

Increased biodiversity can boost yields, by providing services such as pollination, nutrient recycling and predators of pests

IMPROVING AGRICULTURAL SUSTAINABILITY WITH DIGITAL TECHNOLOGY

In recent decades, advancements in agricultural practices have made the large-scale production of cheap and nutritious food possible. However, these practices are often damaging to the environment, making them unsustainable in the long term. Technology is now sufficiently developed that many of these environmental impacts can be reduced or mitigated, by using 'big data' to inform farming management decisions. **Dr Bruno Basso** from Michigan State University and his network of researchers have been exploring how digital technologies could usher in a new era of sustainable agriculture that balances competing economic and social interests while minimising trade-offs.

The Agricultural Revolution is Digital

Consumers today have more choices and easier access to nutritious and inexpensive foods than ever before, thanks to the developments in agricultural technologies that have now become common practices. Machinery, fertilisers, pesticides and irrigation have allowed farmers to grow larger crops with much higher yields, to meet the demands of the growing population.

However, these conventional agricultural practices have damaging consequences for the environment. For example, excess fertiliser that is not used by the crop plants often finds its way into local waterways, disrupting the delicate aquatic ecosystems and causing large algal blooms that suffocate plants and animals. Pesticide usage and loss of suitable habitats have had dire consequences for beneficial insects such as pollinators. Greenhouse gas emissions from agriculture contribute to global climate change, having impacts far beyond the farms' localities.

It is becoming increasingly apparent to farmers, consumers, scientists and policy-makers alike that agricultural practices must become more environmentally sustainable, to ensure our future food security.

Fortunately, much of the technology required to support an agricultural revolution already exists. By combining sensor technologies, satellites, drones and GPS facilitates, collecting detailed information about the health of plants and soil is now possible. Using these tools, crop health can be monitored closely across large fields and at different stages of crop development or between seasons with relative ease.

New powerful analytical tools, such as Artificial Intelligence systems and computational modelling, allow researchers and farmers to incorporate all of this information – or 'big data' – into precise agricultural management plans, which reduce resource wastage and improve environmental sustainability.

‘Filling in the gaps with big data to create the next agricultural revolution will benefit not only the economics of agriculture, but the environment as well. We are only leasing the Earth’s land, so we must leave it in better condition than that in which it was given to us.’

Dr Bruno Basso of the Department of Earth and Environmental Sciences at Michigan State University has been exploring how advanced monitoring, analysing and predictive tools – together called ‘Digital Agriculture’ – can help farmers to balance the complex needs of a growing human population.

‘The best hope for meeting the challenge of sustainable agricultural development lies in the ongoing process of innovation now taking place using modern genetic and information technologies to increase agricultural productivity while balancing economic, environmental and social outcomes associated with agriculture and the food system,’ he says.

Through their extensive research, Dr Basso and his team have demonstrated how digital healthcare for plants and soil, in the form of better management of fertiliser and irrigation, can maintain better crop health throughout its growth cycle and improve environmental sustainability.

Precision Plant Health

Rarely are the fields used to grow crops a uniform, flat area. Even a single field can show significant variations in soil quality, microclimate, elevation and water cycling. These factors impact plant development and can lead to dramatic differences in the health and yield of the crop across the field.

Despite this, conventional agricultural practices usually treat these fields as a homogenous area, for example, by applying nitrogen fertiliser uniformly across the field. Consequently, some plants may not be getting adequate fertiliser to support their growth, while others whose growth is limited by other factors cannot use all the supplied fertiliser, which then finds its way into the surrounding ecosystem.

Dr Basso and his collaborators have been exploring how detailed crop management plans can be produced by combining Digital Agriculture with ‘precision agriculture’ – systems that allow variable inputs of fertilisers and irrigation according to the spatial variability of crop growth.

‘Thus far, algorithm developers for precision management have lacked the data and computational tools needed to convert complex spatial information on soil and plant status into appropriate crop management actions,’ explains Dr Basso. ‘Misinterpretation and misuse of data appears to be a consequence.’ For example, many farmers use precision technologies to increase nitrogen fertiliser application on low-yielding areas of fields in an effort to increase yields, rather than reducing application in these areas to avoid the excess leaching into the surrounding environment.

Dr Basso and his team developed new methods of analysing the spatial and temporal data from satellites and the yield sensors on farming machinery to produce informative yield stability maps. ‘Yield stability maps depict areas within a field characterised by consistently high productivity over time, other areas with consistently low productivity, and other areas where yields are unstable – high one year, low the next,’ Dr Basso explains.

The individualised crop management plans arising from this analysis allow farmers to incorporate not only the productivity of different areas of their fields, but also variations in other factors that affect plant development, such as rainfall, and adjust their crop treatments accordingly. Many previous attempts at prescriptive maps for precision agricultural inputs have been based solely on soil maps, neglecting the interactions between soil, weather, and other farming practices that may significantly impact crop yields in different years.

Dr Basso's evidence-based predictive approach helps to take the guesswork out of crop production and could help to reduce environmental impact. His team demonstrated that if fertiliser application was based on plant demand rather than relying on a uniform application, nitrogen fertiliser use in the Midwest of the USA could be reduced by as much as 36%. Aside from reducing waterway pollution, decreasing fertiliser use also reduces greenhouse gas emissions and energy usage.

Additionally, yield stability maps can also help farmers to re-design fields or areas within fields. Dr Basso suggests that parts of fields that are unprofitable or environmentally unsustainable can be identified and allocated to other purposes, such as wildflower patches to support pollinators and increase biodiversity, thus further increasing the environmental benefits of this approach. In high-yielding areas of the field, farmers can sustainably intensify crop production by increasing fertiliser inputs, knowing that the plants will respond positively.

'Digital Agriculture can truly lead to higher resource use efficiency by reducing losses to the environment and at the same time, increase profitability by removing low areas from production with a precision conservation approach, which should reward farmers for these environmental benefits and ecosystems services,' says Dr Basso.

Barriers and Solutions for Implementation

The agricultural sector currently faces enormous challenges. With the human population expanding, producing enough food to feed everyone is becoming increasingly difficult. Balancing this need with protection of the environment, which we all rely on, often leads to tough trade-offs.

'The current agricultural system needs to adapt and become more efficient on less farmland, and under climate change threats, in order to feed a growing population,' says Dr Basso. 'Farmers must consider their personal ability, financial stake, and a myriad of environmental considerations before leaping into a new practice or adopting innovative technology.'

Farmers are generally very aware of the negative impacts agricultural practices have on the environment, but it is important to recognise that policymakers and consumer demands also play a large role in shaping agricultural systems. While Digital Agriculture is still developing, through the work of researchers including Dr Basso, precision agriculture has been possible for around three decades. However, it has thus far failed to produce the expected improvements in environmental performance of farms. Dr Basso suggests that this may be, at least in part, due to the lack of effective policies to incentivise the use of precision agriculture technologies.

To ensure Digital Agriculture does not suffer similar failures, appropriate policies, subsidies and investments will be necessary to encourage behavioural changes in both consumers and producers. Thus, at its core, the mission of the Digital Agricultural revolution is to balance complex economic and social needs by incorporating agriculture, science, technology, policy and education.

Additionally, to ensure the success of sustainable technologies across the globe, they need to be economically viable for the large-scale systems of commercial agriculture, as well as the smaller-scale systems common in developing countries. Public policies and investments could also help to support the development of sustainable technologies that achieve this goal. Dr Basso notes that until investments are made towards this, progress is likely to remain limited.

Fortunately, tools such as Digital Agriculture are advancing rapidly. 'Filling in the gaps with big data to create the next agricultural revolution will benefit not only the economics of agriculture, but the environment as well,' concludes Dr Basso. 'We are only leasing the Earth's land, so we must leave it in better condition than that in which it was given to us.'

Meet the researcher

Dr Bruno Basso
Department of Earth and Environmental Sciences
Michigan State University
East Lansing, MI
USA

Dr Bruno Basso earned his PhD in Crop and Soil Sciences from Michigan State University, before continuing onto an assistant professorship in the Department of Crop Systems at the University of Basilicata, Italy. He currently holds the position of University Foundation Professor in the Department of Earth and Environmental Sciences at Michigan State University. His research interests focus on how to improve the sustainability and yields in agricultural systems, in particular, by using digital technologies and computational modelling. Dr Basso has received numerous academic awards and fellowships for his research, has been invited to present his work at meetings across the world, and has published nearly 200 articles in peer-reviewed journals. Additionally, Dr Basso is the co-founder and chief scientist of CiBO Technologies, an innovative land intelligence system that utilises geospatial technology to identify the value and environmental sustainability of a piece of land.

CONTACT

E: basso@msu.edu
W: http://basso.ees.msu.edu

FUNDING

US National Science Foundation
US Department of Agriculture - National Institute for Food and Agriculture (USDA-NIFA)
US Department of Energy, Office of Science, Office of Biological and Environmental Research
US Agency for International Development
Bill and Melinda Gates Foundations
Michigan Corn Marketing Program
Michigan Wheat Program
Michigan Potato Industry Commission
Michigan State University AgBioResearch

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MICHIGAN STATE UNIVERSITY

MODELLING A SUSTAINABLE FUTURE FOR LIVESTOCK PRODUCTION

Intensive livestock farming has contributed to environmental degradation across the globe, and is also a major source of greenhouse gas emissions. However, meeting the protein demands of a growing global population requires further increases in the food supply. **Dr Luis Tedeschi** and his team from Texas A&M University and Texas A&M AgriLife Research have been studying the sustainable intensification of livestock production, utilising modelling-based approaches. They consider whether these tools can be used to increase production efficiency while minimising environmental impacts, helping to preserve and regenerate the natural resources that form the basis of the industry, for future generations.

Livestock and the Environment

Most of our current food production systems are based on maximising productivity and profitability with inadequate concern for protecting or regenerating the environment in the process. With a world population that is predicted to reach 9.55 billion by 2050, increasing pressure is being placed on global food production. Doing so while reducing the impact on the environment requires crop, soil and animal scientists around the world to come up with quick and effective solutions.

Livestock farming alone is one of the critical global contributors to greenhouse gases – accounting for up to 14% of emissions, depending on the production system. Other negative environmental impacts of the industry include nutrient run-off that pollutes water bodies, soil erosion, and the consumption of non-renewable resources.

These adverse environmental changes quickly offset improved agricultural productivity, through degradation of soil quality, increased warming, the resurgence of diseases and depletion of biodiversity, among many other outcomes. Indeed, meeting the future food requirements of our global population is not possible without environmental protection.

In short, to ensure that human population growth does not outstrip our ability to produce food, we must look after the natural resources that are at the very heart of the industry – so that they will be available for future generations. Furthermore, it is clear that any increase in food production must be achieved through enhanced yield, rather than expanding land area, as the latter would further increase the burden on the environment.

Sustainable Livestock Intensification

Dr Luis Tedeschi and his team of researchers from Texas A&M University are working to evaluate whether livestock production could be intensified in a sustainable way, to help

feed our growing population without the need to expand our agricultural land usage. Their work involves identifying the key areas where changes or improvements can be made, modelling what the impacts of these changes might look like, and how the resultant decision support tools can be integrated to help livestock farmers improve their efficiency.

The team believes that environmental protection is paramount for providing good livelihood standards for people and ensuring the survival of our species (and many others) in centuries to come. A sustainable system has the ability to coexist with other systems, and has the

'The use of these modelling-based decision support tools, together with innovative pasture systems, in a more integrated smart farming approach, could be the next step toward improving the sustainability of livestock systems.'

resilience to recover after it has been disturbed. These are qualities that future food production systems will need to exhibit in order to continue to prosper in the face of global climate change.

If sustainable intensification of livestock production is adopted, it could lead to greater production yields through more efficient use of resources, while reducing negative impacts on the environment. It provides opportunities for increasing animal and crop production per unit of area, while employing sustainable production alternatives that fully consider what the team describes as the three pillars of sustainability: planet, people, and profit.

Targeting Technology to Increase Sustainability

Animal nutrition is one of the major focus areas identified by Dr Tedeschi for improving livestock productivity in a sustainable way. Ruminant animals, such as cattle and sheep, acquire nutrients from plant-based feed by fermenting it in their rumens prior to digestion.

The goals of his research team in studying the enhancement of ruminant nutrition are to improve productivity, reduce resource use, and protect the environment. Dr Tedeschi and collaborators believe that feed efficiency may be the single most crucial variable that can drive up yields while concurrently lowering the carbon footprint of ruminant production by reducing greenhouse gas emissions.

This prioritises the identification and selection of feed-efficient animals, feeding systems, and technologies that improve nutrient use efficiency. To explore the various factors and their interactions, Dr Tedeschi employs a computational modelling approach. 'System modelling is a powerful tool in the area of nutrition as a whole, because it accounts for many variables and the interactions involved in identifying sustainable systems in each situation,' he says.

Dr Tedeschi's research group believes that there is scope for these models to become a core component of precision farming applications, including automatic feeding systems. However, it is becoming increasingly important to view individual models as part of the overall, more holistic, systems-based approach, favoured by the team.

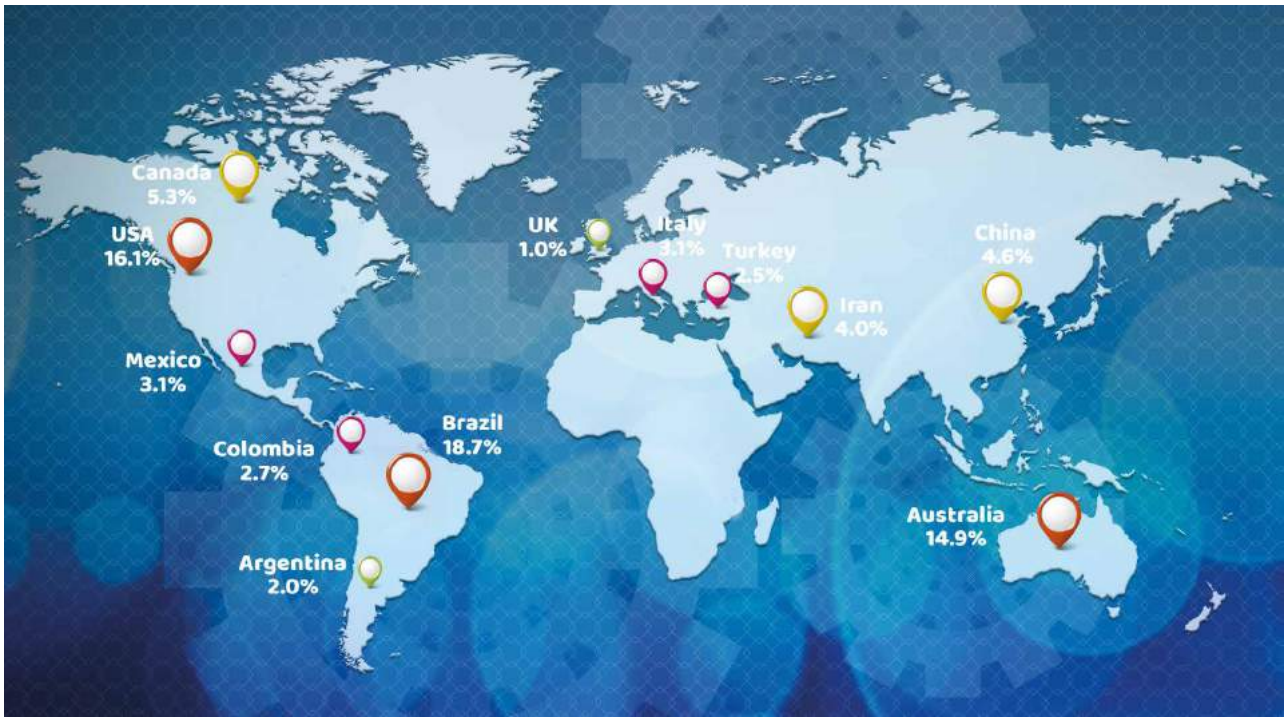
'It will be necessary to combine a range of models from different fields, including animal, soil, crop and weather sciences,' says Dr Tedeschi. 'At the moment, these mathematical models are difficult to integrate, but such integration is needed for the long-term prediction of production policies.'

These models could include areas as diverse as utilising behaviour monitoring techniques as a solution for enhancing feeding to optimise milk yield. Other models use innovative but practical approaches to identify synergies between different types of grazing animals, to help improve economic feasibility and counter resource limitations.

'The challenge is combining these models into an integrated suite of decision support tools,' says Dr Tedeschi. Advances in technology for improved agricultural production have led to so-called smart farming, harnessing sensor and communication technologies, to increase production efficiency. 'Utilised in this way, mathematical modelling as the basis of decision support tools can be used to process and interpret large amounts of data from multiple agricultural technologies to overcome environmental, technical and economic production challenges,' he concludes. Furthermore, as Dr Tedeschi stated in the 2020 Ruminant Nutrition System book, given the high-processing capacity of modern computers, interpreted computer programs, such as R and Python, ease modelling collaboration across disciplines through a universal language that facilitates the transferability of knowledge to the artificial intelligence dominion.

Is Sustainable Livestock Intensification Possible?

Despite tremendous advancements in the livestock sector, the Texas A&M University team believes that additional opportunities exist to improve livestock production around the globe. 'Scientific progress in ruminant production, through the use of decision support tools, has been significant and tangible,' says Dr Tedeschi. 'However, these achievements are only just becoming apparent because we are still learning how to connect the concepts involved.'



Visitor map for Dr Tedeschi's nutritionmodels.com website, with over 125,000 visits globally.

If utilised as a part of a more holistic and connected approach, these decision support tools could become more critical than ever. They have the ability to enable users to quickly evaluate multiple scenarios of production and choose options that are more acceptable, sustainable and resilient. Smart farms and advancing technology combined with modelling have the potential to identify high leverage solutions (small changes that produce significant results), such as individual supplementation of dairy cattle.

'The use of these modelling-based decision support tools, together with innovative pasture systems, in a more integrated smart farming approach, could be the next step toward improving the sustainability of livestock systems,' says Dr Tedeschi. 'Using these techniques, producers could evaluate many production alternatives and choose the best solution for each specific condition and desired outcome.'

Future iterations and development of these tools must account for the effects of climate change on animal welfare and nutrient needs and productivity. They must also include increased levels of consumer demand for high-quality, protein-rich food, while at the same time minimising livestock's environmental carbon and water footprint. 'We must incorporate state-of-the-art data and analytical techniques such as artificial intelligence and machine learning,' says Dr Tedeschi. 'This will help to improve the accuracy and precision of our decision support systems.'

Forecasting in modelling terms is not an exact science and relies heavily on past, current and new knowledge to improve outcomes. Advances in nutritional sciences include a better understanding of how the quality of animal products can be increased, the development of new feeds and feeding strategies, and revisiting longstanding technologies. Future improvements in the understanding of animals' microbiomes may also enable scientists to increase fermentation efficiency.

Developments in remote sensing and ground-based instrumentation, communications, and weather forecasting technologies will also aid in the continued improvement of early warning systems to help livestock producers to reduce risk and adapt to the changing environment. Broad utilisation of sensor technologies will allow scientists to collect real-time data and, when combined with mathematical modelling, decision support systems will become an indispensable tool for managing livestock production, with the possibility to automate some decisions on the farm, such as feeding schedules and early disease detection.

In addition to scientific advancements, the team also highlights the need to address multiple facets within animal agriculture systems, especially in economically and environmentally challenged environments, and that education will be a necessary first step to solve many current and future challenges. This must be followed by investing in scientifically proven feed-efficient animals within the world's economically marginal populations.

It is clear overall, therefore, that sustainable intensification is not the result of improved biological and physical processes alone; it requires the intervention of human ingenuity to manage the system appropriately and intelligently in an integrated, holistic way. However, modelling-based integrated decision support systems could form the backbone of the future sustainable intensification of the livestock industry.

Meet the researcher

Dr Luis Tedeschi
Department of Animal Science
Texas A&M University
College Station, TX
USA

Dr Luis Tedeschi is a Professor in Ruminant Nutrition in the Department of Animal Science at the Texas A&M University. He holds a Bachelor's degree in Agronomy Engineering and a Master's degree in Animal and Forage Sciences from the University of São Paulo, and a PhD in Animal Science from Cornell University. Dr Tedeschi is a Texas A&M AgriLife Research Faculty Fellow and Texas A&M University Chancellor EDGES Fellow. Dr Tedeschi's research is focused on the integration of scientific knowledge of ruminant nutrition that has been accumulated over the years to solve contemporary problems. His areas of interest include energy and nutrient requirements of grazing and feedlot animals, growth biology and bioenergetics, modelling and simulation of decision support systems and evaluation of models. To date, thousands of people around the world have benefited from Dr Tedeschi's innovative models, and his Nutrition Models website has been visited over 125,000 times. Dr Tedeschi has published more than 250 papers in peer-reviewed journals and book chapters, and presented at more than 80 conferences and workshops worldwide on modelling nutrition. He has also received numerous awards for his research, including the J. William Fulbright Foreign Scholarship Award and the Sir Frederick McMaster Fellowship Award.

CONTACT

E: luis.tedeschi@tamu.edu
W: https://animalscience.tamu.edu/people/tedeschi-luis/
W: https://animalscience.tamu.edu/quantifiable-animal-performance/
W: https://www.nutritionmodels.com/

KEY COLLABORATORS

Alberto S. Atzori, University of Sassari, Italy
Antonello Cannas, University of Sassari, Italy
Gordon E. Carstens, Texas A&M University
Mozart A. Fonseca, University of Nevada
Danny G. Fox, Cornell University
Hector M. Menendez III, USDA-ARS
James P. Muir, Texas A&M AgriLife Research
T. G. Nagaraja, Kansas State University
Monte Rouquette, Texas A&M AgriLife Research

FUNDING

Texas A&M AgriLife Research.

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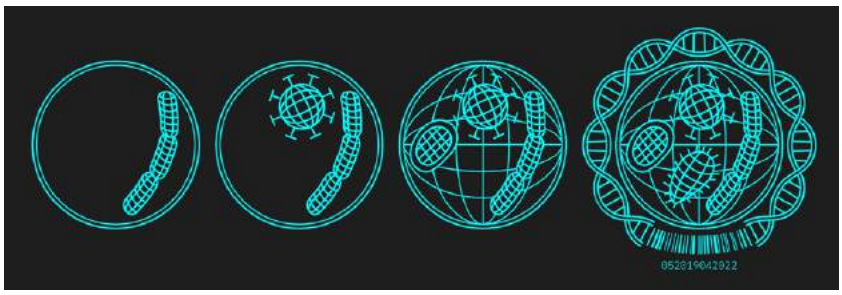
TEXAS A&M UNIVERSITY
TEXAS A&M AGRILIFE RESEARCH
QUANTIFIABLE ANIMAL PERFORMANCE

BEYOND THE ANTHROPOCENE: ARE WE ENTERING A 'MULTISPECIES TURN'?

A multispecies approach to scientific, cultural and anthropological studies is in direct opposition to traditionally held anthropocentric views of human superiority. However, **Drs Stefan Rieger** and **Ina Bolinski** from the Ruhr-University Bochum are working to scrutinise the collaborations between species as diverse as humans, animals, plants, fungi, insects and microbes, and believe that we could be at the beginning of a 'Multispecies Turn' in our history. Through their research in media studies, they show that exploring such collaborations could become a necessity in solving many societal challenges, particularly in the area of precision agriculture.



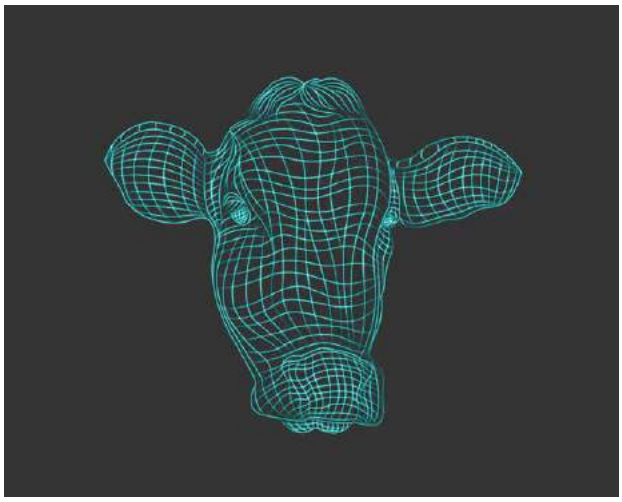
Back to Nature – But Not as We Know It

Anthropocentrism is the belief that human beings are the most important factor in the Universe, and interprets the world in terms of human values. Traditional and long-held anthropocentric views of the world therefore assume human superiority over animals, and indeed any other living beings, and non-living entities. Moreover, the naming of our current epoch, as the 'Anthropocene' places human beings at the centre of the period of time in which we exist.

In contrast, exploration of multispecies societies is a recent trend that has begun to address the involvement of non-humans in what are typically considered human cultural practices. The central facet of this multispecies approach is the recognition that humans are not singular, unified agents. Rather, alongside our human cells, we are comprised of a huge array of non-human entities, including bacteria, viruses and fungi – without which we could not survive.

Dr Stefan Rieger and Dr Ina Bolinski at Ruhr-University Bochum think that the collaborations across species that are at the centre of this multispecies view are about to challenge well-established taxonomical and epistemological divides between humans, animals, plants, cultural artefacts and the increasingly mediatised environments in which we, and they, exist. They argue that the long-held anthropocentric position, which emphasises humankind's island position and pre-eminence above other living beings, no longer works under the pressures of human-animal studies and post- and trans-human areas of thought.

Dr Bolinski and Dr Rieger believe that we should be looking at expanding the actors within our environment, and that non-human species at varying scales influence many aspects of our culture, practice and behaviour. 'The expansion of virtual reality in particular provides opportunities to immerse oneself in other forms of life and find a new perspective,' says Dr Rieger. In these worlds, it becomes possible to become, for example, an animal, or a plant, and to feel an empathy with other species within the virtual media, which has itself become part of the individual's environment.



'With this shifting focus towards non-human actors, the presumably obsolete concept of holism, and viewing the world holistically, re-emerges as a fruitful construct,' suggests Dr Rieger. 'These changes result in what can be described as a "Multispecies Turn" within contemporary culture.'

Dr Bolinski and Dr Rieger describe this 'Multispecies Turn' as being located in diverging fields such as natural and social sciences, arts and politics. Media studies, with a focus on cultural techniques, can play a crucial role with regard to this 'Turn', as this field often reflects on collaborations that take place with the help of media technologies, or within medial environments of various living and non-living actors.

'Be it dogs as sensors for cancer diagnostics or bacterial DNA as data storage – biological actors have already surpassed technological variants in various fields,' explains Dr Rieger. 'But what is happening between species also needs theoretical reflection – a deficit which is also mirrored in the establishment of new fields of research such as Animal-Computer-Interaction.'

Practical Applications of a Multispecies Approach

Alongside their investigations into how to close the theoretical gap between species and their interactions, Dr Rieger and Dr Bolinski are also concerned with addressing the ethical and political implications of the multispecies. The new forms of mixed society generated by this approach include a diverse range of actors such as humans, plants, animals and artefacts, each of which needs careful consideration, and many activities and interactions for which there may not be precedents.

Two particularly suitable examples of the team's area of focus are herd management and ambient assisted living (AAL), and the role that a wide range of human and non-human actors could have in their future development. These two areas, which at first glance might appear wildly differing, exhibit many parallels and crossovers when considered within the context of a multispecies approach.

'In respect to how their data is processed, humans and animals are related,' says Dr Bolinski. 'Technological possibilities of measuring space concern livestock farming as well as the design of human living environments. Processing of data relating to livestock breeding allows us to meet consumer protection standards – however, at the cost of altering the status of animals themselves. Home automation systems (often using the same technology) allow us to preserve the autonomy of people requiring care – but at the cost of delegating some of this autonomy to technology.'

In both areas, fundamental questions are posed concerning current and future societal challenges, including for example rising costs of healthcare, climate change and intensive farming. But they also raise questions for media theory, where the relations of humans and animals to their technological environment are conceived in the face of new media that are invisible, pervasive and reliant on big data.

In terms of monitored herd management, Dr Bolinski asks, what are the implications of animal digitalisation and data collection – on the one hand for categorical determination of culture and nature, and on the other hand for the self-image of humans as a system component of changing environments?

With increasing herd sizes and more extensive management tasks, radio frequency identification (involving injecting a microchip into animals) can be coupled with other systems, such as automatic feeding systems, milking systems, or weighing, loading and sorting facilities, to create processes controlled without human labour. This offers a new perspective when additional functions in the technology of animal identification can be integrated.

Sensors and measuring systems allow body temperature, heart rate, pH values and hormone profiles to be determined in predefined time periods. These values, as well as activity patterns, location analysis and data on stress levels, provide information about the condition and health of an animal. Using similar techniques, procedures in which the appropriate technology is built into clothing mean that comparable forms of health monitoring can also be used for humans in ambient assisted living.

The increasing mechanisation and penetration of technology into the biological arena make previously sharp boundaries blur almost entirely so that it can no longer be clearly determined what is natural and what can be assigned to culture. This is the case with electronic animal identification, and Dr Bolinski argues that microchips injected into animals can no longer be seen as just an object.

'The technical artefact and the "natural" animal also have a new status,' states Dr Bolinski. 'The working hypothesis of our material studies is that with the insertion of the microchip

in the animal body to influence the "natural", the technical and biological components together form a new hybrid unit.'

Through modern GPS technology and data collection and transfer, such 'smart' farming can be extended to encompass the whole farm enterprise, for example, providing data about the composition and movement of the herd structure as a whole. Such data collection allows various management practices to be employed, such as virtual fences that replace physical boundaries completely. This means that entire environments or rooms (in the case of technology-assisted living) become smart and change the living environment for all.

Within smart farming, soil and animal management are no longer separate from each other. Using precision farming techniques, sensors determine values for soil moisture, sunlight and wind conditions, and automatically control irrigation systems. Performance and individual needs of both crops and animals are monitored and adjusted, while data are provided instantly to actors further down the supply chain.

'So-called virtual farming is becoming increasingly common-place, but there are challenges that must be addressed,' explains Dr Rieger. 'These include the requirement for mediation between the diverse range of actors involved, and how we deal with the ever-increasing amounts of data generated.'

Addressing Future Challenges with Multispecies Solutions

As illustrated by Dr Bolinski's example of the virtualisation of farming, the development of new mechanisms for dealing with large amounts of data is integral to an increasingly digitised multispecies approach. 'The requirements of "the memory of the future" are obvious,' says Dr Bolinski. 'Data should be easy to reproduce, and above all, saved permanently. The data should also escape the "digital death" caused by unusable storage media and hardware and software that are no longer available.'

With this in mind, Drs Bolinski and Rieger suggest that in a truly multispecies approach, we should turn our attention to bacteria as a possible solution. Many bacterial strains have properties such as robustness, longevity and rapid reproduction – qualities that make them appear to be an almost predestined choice for forming an efficient, expandable and living data storage solution. In fact, new calculations show that up to 215,000 terabytes can be archived in just one gram of organic matter.

'Tasks still reserved for electronic media today could be taken over by cells whose genes act as an information archive,' says Dr Bolinski. 'Bacteria have a great future as biological storehouses. And more than that – they are living archives.'

The new multispecies perspective on the world, discussed by Drs Rieger and Bolinski, therefore positions humans as no longer acting alone, but instead embedded in diverse collaborative communities. Their view sees the dawn of a new era – one with much greater reliance on, and interaction with, a broader range of species.

In this context, it is important to separate the use of media as being exclusively by humans, and to transfer it to other ways of being – for example from Human-Computer-Interaction (HCI) to Animal-Computer-Interaction (ACI) or Plant-Computer-Interaction (PCI), and further still, to Human-Computer-Biosphere-Interaction (HCBI). Such movements towards cross-species communication and collaboration, as well as the recognition of their interplay with the technical environment, are part of post-humanistic thinking.

With a proper distance from anthropocentrism, living environments could be conceived in which people and animals, machines and plants, real and virtual, aren't categorised taxonomically and ontologically, but exist together in a dynamic of collaborations and interactions that are entangled together.

In a world where humans are not top and centre, multispecies collaborations could provide the mechanisms and opportunities for advancement – potentially taking us past the human-induced limits of today. Furthermore, challenges, and indeed crises, such as our changing climate, feeding a growing world population or looking after our aging population, may be seen as cross-species problems, with the solutions actually being reliant on this multispecies approach.

CREDIT: Damian Gorczany

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Meet the researchers

Dr Stefan Rieger
Institute for Media Studies
Ruhr-University Bochum
Bochum, Germany

Dr Ina Bolinski
Institute for Media Studies
Ruhr-University Bochum
Bochum, Germany

Dr Stefan Rieger has held the position of Professor of Media History and Communication Theory at the Ruhr-University Bochum since 2007. His doctorate was in data processing and mnemonics, and his thesis examined the relationship between media and anthropology. The current focus of his work and publications is on the history of science, media theory and cultural techniques. Since May 2019, he has worked on the DFG-funded project 'Cross-species collaborations: To the Multispecies Turn in Media Studies' with Dr Ina Bolinski, and the pair have run a series of workshops and conferences covering topics as diverse as plant communication and human-robot interactions.

CONTACT

E: stefan.rieger@rub.de
W: https://ifmlog.blogs.ruhr-uni-bochum.de/ifm/personen/prof-dr-stefan-rieger/

Dr Ina Bolinski has worked as a Research Associate at the Ruhr-University Bochum since 2013. Prior to this, she was a Junior fellow of the DFG research group 'Media Cultures of Computer Simulation' at the Leuphana University in Lüneburg. Dr Bolinski's main areas of research include media history of electronic animal identification and data-based herd management, living data storage, animals in digital media and human-animal studies. Since May 2019, she has been working on the DFG-funded project looking at a 'Multispecies Turn' in Media Studies detailed above, with Dr Stefan Rieger.

CONTACT

E: ina.bolinski@rub.de
W: https://ifmlog.blogs.ruhr-uni-bochum.de/ifm/personen/ina-bolinski/

KEY COLLABORATORS

Forschungsinitiative Tiertheorien (FITT)
https://www.uni-kassel.de/fb05/fachgruppen/geschichte/sozial-und-kulturgeschichte-human-animal-studies/kooperationen/forschungsinitiative-tiertheorien-fitt.html

RUHR UNIVERSITÄT BOCHUM

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FUNDING

DFG – The German Research Foundation

EXPLORING ALTERNATIVES TO ANTIBIOTICS FOR REDUCING SALMONELLA IN POULTRY

Salmonella remains the leading pathogen of food safety concern in the US, with poultry being the main vector. For many years, poultry producers have relied on antibiotics to curtail the prevalence of pathogens in their flocks. However, consumer concerns and the rise of antimicrobial resistance are leading to the withdrawal of antibiotics, leaving farmers in unchartered territory. **Dr Adelumola Oladeinde** at the US Department of Agriculture is collaborating with researchers from the University of Georgia and Colorado State University to develop novel techniques for reducing Salmonella in chickens. Their work focuses on preventing infection and predicting risk in antibiotic-free production.

Salmonella: A Long-standing Problem

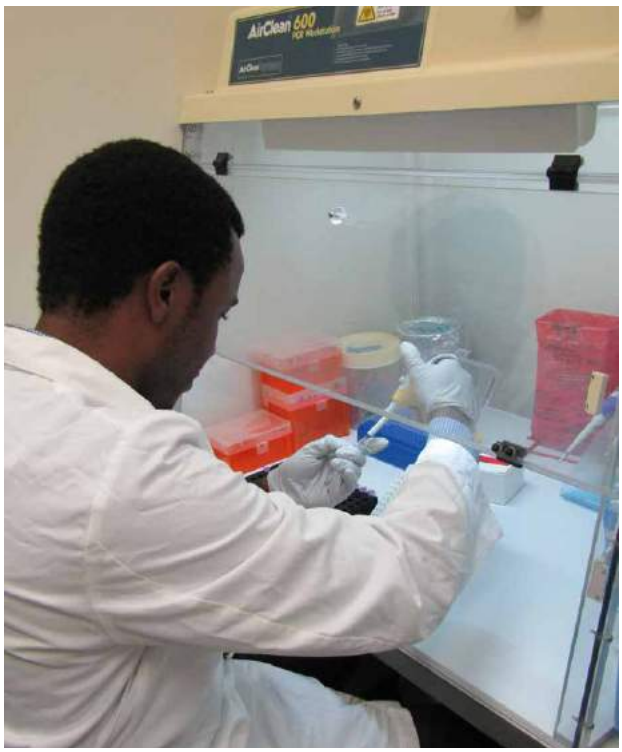
The US supports a multi-billion-dollar poultry industry and is currently the world's largest producer of broilers – chickens bred and raised specifically for meat production. However, broiler production in the US and worldwide is facing emerging challenges of animal health and food safety. Concerns over the human-health impacts of using antibiotics against bacteria such as Salmonella are leading to a push towards antibiotic-free broiler production. However, this could put birds at high risk of infection and increase the likelihood of food contamination.

Each year, Salmonella infects around 1.2 million people and results in economic losses of between 2.3 and 11.3 billion dollars in the US. Salmonella infection (salmonellosis) is a bacterial disease that affects the human intestinal tract and is usually characterised by the acute onset of fever, abdominal pain, diarrhoea, nausea and sometimes vomiting. Humans are most frequently infected through contaminated water or food, with poultry being the major cause of Salmonella infection.

In poultry production, the practice of using antibiotics to treat avian diseases can lead to the survival and subsequent proliferation of strains of bacteria that are resistant to the antibiotics used. These bacteria can then be transferred to consumers through meat and eggs.

Alongside the use of antibiotics, vaccination of broiler chickens is another common intervention adopted by producers to prevent diseases. However, there are currently no vaccines that can protect against all strains of Salmonella.

The prevalence of Salmonella in poultry has remained unchanged for many decades, leading Dr Adelumola Oladeinde at the US Department of Agriculture's Agricultural Research Service (USDA-ARS) to seek a novel



approach to reducing and identifying Salmonella infection in poultry production. Working with a multidisciplinary research team from the USDA-ARS, University of Georgia and Colorado State University, Dr Oladeinde has focused his research on Salmonella Heidelberg – one of the main strains of Salmonella that causes food-borne outbreaks.

'Infections caused by Salmonella Heidelberg are also more invasive than other strains, and Salmonella Heidelberg associated with poultry tends to carry antibiotic resistance and virulence genes,' says Dr Oladeinde. 'Therefore, Salmonella Heidelberg represents a model organism for testing the mechanisms that we have been developing.'

The team's research so far indicates that Salmonella is a hardy pathogen that is nearly impossible to get rid of after it successfully colonises a broiler farm. 'Our work therefore shows that it may be worthwhile directing resources towards prediction and prevention rather than decontamination or vaccination,' explains Dr Oladeinde. 'Consequently, we are focusing our efforts in two key areas – examining how the type of poultry litter used in broiler houses can prevent infection and development of antibiotic resistance, and devising a flock health monitoring system that can help us to predict infection risk sooner.'

Importance of the Litter Microbiome

Raising billions of broilers each year requires over 10 million metric tonnes of poultry litter annually in the US. This litter is composed of wood shavings, rice hulls, or sawdust, and becomes mixed with chicken faeces, uric acid, feathers and feed. Because of the increasing cost of bedding materials, and to reduce waste, it is common and well-accepted practice in the US to recycle these materials over multiple flocks for a year or longer.

Dr Oladeinde and his team wanted to study the impact of using fresh or recycled bedding material on the incidence of Salmonella within the flock and its impact on the development of antibiotic resistance – even in the absence of antibiotic use. The team inoculated fresh and reused broiler litter in the lab with different strains of Salmonella and monitored it for 14–21 days – collecting and characterising the Salmonella strains surviving and in the broiler litter.

They also carried out experiments with live birds – rearing chickens carrying Salmonella Heidelberg on either fresh or recycled litter. They found that the microbiome (collection of microorganisms) present in the reused litter negatively correlated with the populations of antibiotic-resistant Salmonella Heidelberg in the chickens' guts, compared with broilers raised on fresh litter. 'This suggests that reused litter promotes an unfavourable microbiome for Salmonella carrying antibiotic resistance,' says Dr Oladeinde.

The team found that Bifidobacterium was the main type of bacteria that was in significantly higher concentrations in the gut of birds raised on reused litter versus fresh litter. They are now carrying out further work utilising the novel information gained from this study to identify the specific beneficial microbes found in the litter microbiome. These microbes could potentially be used as an alternative to antibiotics for Salmonella reduction.

'Reducing antibiotic use alone in poultry is likely insufficient to limit the development of antibiotic resistance,' says Dr Oladeinde. 'A beneficial microbe that can significantly reduce antibiotic-resistant Salmonella in live broiler chickens would provide a powerful new tool to improve food safety in chickens raised without antibiotics.'

Overall, the team's work shows that the litter material used for growing broilers has a significant impact on the developmental process of the chicken gut and its eventual microbiome. Therefore, interventions that can reduce the population of antibiotic-resistant Salmonella in litter have the potential to limit their transfer to the chicken gut.

Predicting Infection to Reduce Risk

As well as their research into preventing Salmonella infection and reducing the number of antibiotic-resistant strains of Salmonella in poultry, Dr Oladeinde and his team have also been investigating new ways to predict the Salmonella risk within a flock.

Previously, the asymptomatic nature of Salmonella infections has made it impossible for producers to determine whether a flock is infected. However, Dr Oladeinde's work in identifying the differences between the microbiomes of birds infected with Salmonella and those of uninfected birds could be key to recognising behavioural and physiological differences required for predicting infection.

Wider studies have shown that some 'beneficial' bacteria identified by the team in the microbiomes of birds raised on reused litter, including Bifidobacterium, can alleviate anxiety and depressive-like symptoms in mice and humans, indicating that the gut microbiome can have a positive impact on the brain.

Based on these studies, Dr Oladeinde hypothesises that even in the absence of obvious symptoms, chickens infected with Salmonella Heidelberg will exhibit social cues that are different from uninfected birds. 'The nature of broiler production – growing of more than 20,000 chickens for six to seven weeks in concentrated animal feeding operations makes it difficult for caretakers to manually detect these early cues that could be associated with the onset of an infection,' says Dr Oladeinde. 'That's what led us to embark on development of an automated vision-based Salmonella Predictor or vbSALP, which should be able to identify and locate individual birds with Salmonella infections within the first two weeks of life.'

The proposed vbSALP will use advanced imaging technologies to collect information on poultry health and social cues associated with Salmonella infection, including behaviour traits, bird weight and body temperature. Microbiology and molecular genetics will also be used to determine Salmonella prevalence, virulence and antimicrobial resistance status. The vbSALP will also employ machine learning to associate the image parameters with the flock's Salmonella status.

The vbSALP is currently in the early stage of development and the team has been training the system to identify social cues of Salmonella-free broiler chickens raised without antibiotics, using two on-site computers and twelve cameras in a small-scale broiler house.

So far, the team has generated 3528 hours of video footage, which they are analysing to develop prediction algorithms. Subsequent stages of development will include testing vbSALP on images of broiler chicks that have been inoculated with Salmonella Heidelberg strains and optimising vbSALP for a verification test in a commercial broiler house. Their goal is to make vbSALP available as a USB stick that can be used by farmers with little expertise in computer use – providing a practical and cost-effective tool for improving animal production and food safety.

Aside from Salmonella detection, the team plans to upgrade the technology for future use in animal welfare and other disease monitoring applications. It therefore has the potential to provide a solution for the early detection of animal disease and infection over a large geographic scale, and with significant economic gains.

'If our proposed early prediction tool is successfully developed and adopted by just 5% of US chicken producers, it could reduce the number of Salmonella-carrying chickens at slaughter by 90 million annually,' says Dr Oladeinde. 'This will significantly improve food safety and reduce the need to recall chickens because of Salmonella contamination.'

The combination of the team's research into the poultry microbiome, together with the development of the vbSALP to detect infection risk, has the potential to provide a novel approach to Salmonella prevention and prediction that does not rely on host immune response, antibiotic use or vaccine effectiveness.

'The poultry industry and the American consumer care deeply about food safety, animal health and welfare,' summarises Dr Oladeinde. 'This research could provide the practical means for producers to improve animal production and food safety by reducing the risk of Salmonella infection in antibiotic-free production.'

Meet the researcher

Dr Adelumola Oladeinde
National Poultry Research Center
USDA-ARS
Athens, GA
USA

Dr Ade Oladeinde gained his PhD in Environmental Health Science in 2017 from the University of Georgia, under the direction of Professor Erin Lipp and Dr Marirosa Molina (USEPA). Before joining USDA's Agricultural Research Service (USDA-ARS) as a Research Microbiologist, Dr Oladeinde was an ORISE Postdoctoral fellow under the mentorship of Dr Kimberly Cook (USDA-ARS). Dr Oladeinde's research within the Bacterial Epidemiology and Antimicrobial Resistance Unit of USDA-ARS focuses on food safety – specifically the microbial ecology of food-borne pathogens and the development of antimicrobial resistance in poultry production settings. Since joining USDA-ARS, Dr Oladeinde has conducted studies to evaluate the survival and evolutionary ecology of Salmonella in the chicken gut and litter, utilising Big Data to decipher the interplay between the poultry microbiome, mobile genetic elements and occurrence of multidrug resistant Salmonella.

CONTACT

E: ade.oladeinde@usda.gov
W: www.ars.usda.gov/people-locations/person/?person-id=53859

KEY COLLABORATORS

Zaid Abdo, Colorado State University
Samuel Aggrey, University of Georgia
Lilong Chai, University of Georgia
Casey Ritz, University of Georgia
Torey Looft, USDA-ARS
Nelson Cox, USDA-ARS
Moussa Diarra, AAFC, Canada

FUNDING

USDA-ARS

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USDA ars Agricultural Research Service

SECURING A SUSTAINABLE FUTURE FOR AQUACULTURE

To help feed a global population of the magnitude expected by 2050, fish farming will need to increase dramatically. Two main factors limiting the expansion and future sustainability of the aquaculture industry are finding feed replacements that have equivalent or improved nutritional benefits, and preventing disease. Over the last 20 years, **Dr Ken Overturf** and his team at the USDA's Agricultural Research Service in collaboration with the Aquaculture Research Institute at the University of Idaho have been working to establish a genetic enhancement program for rainbow trout, with the aim of helping to boost global fish production in a sustainable manner.

An Industry Under Pressure

Aquaculture – the farming of fish, crustaceans, molluscs, aquatic plants and algae – is the fastest growing food-producing sector globally. It now provides close to half of all fish supplies for direct human food consumption – having risen from just 13% in 1990.

As the global population is expected to reach almost 10 billion by 2050, the Food and Agriculture Organisation (FAO) of the United Nations projects that food supplies will need to increase by 70% over current production. The contribution of aquaculture is expected to increase further, particularly with harvests from traditional fisheries being overexploited or depleted.

The fundamental question is whether the industry can expand with sufficient speed, yet remain sustainable. The two main factors determining aquacultural sustainability are fishmeal and fish oil replacements in feeds with alternative cost-effective ingredients, and the prevention and management of disease.

Manufactured from wild-caught fish and by-products from fish processing, fishmeal is a primary source of protein in aquacultural feeds. With the growth of aquaculture, there is insufficient fishmeal available to include in feeds at the levels currently used. Therefore, there is a great need to incorporate alternative sources of protein and oil into fish feeds. In several reported instances, higher levels of alternative protein sources, such as plant protein, have led to reduced growth, decreased feed efficiency, and higher mortality. Even so, replacing the protein in fish feeds with plant protein lessens the industry's dependence on fishmeal, while also potentially reducing the amount of phosphorus in facility effluents, and thus decreasing water pollution.

The second major challenge facing global aquaculture is losses due to disease. In 2017 alone, total losses of all trout intended for sale amounted to 31.4 million fish, with diseases accounting for an astounding 94% of these losses. While preventative measures such as biosecurity, vaccinations and medications are used to help combat disease, there remains considerable room for improvement in both strategic efforts and in our fundamental understanding of fish diseases.

CREDIT: Stephen Ausmus

Improving Aquacultural Production

Over the last 20 years, Dr Ken Overturf from the United States Department of Agriculture's Agricultural Research Service (USDA-ARS) has been exploring ways to boost global fish production in the aquaculture industry. His team and his collaborators in the University of Idaho's Aquaculture Research Institute have conducted a range of in-depth studies, focusing on nutrition and disease, at the Hagerman Fish Culture Experiment Station.

'The sustainable development of aquaculture is dependent on successful nutritional innovations and improvements in animal metabolic performance,' says Dr Overturf. 'A holistic approach incorporating the evaluation of production practices, fish physiology, feed formulations, disease therapeutants, and genetics are necessary to determine nutritional innovations and for optimising animal health, quality and performance, reducing feed costs and, ultimately, fostering sustainability of aquaculture.'

Through their work, his team has found that alternative food sources and management of disease must be examined in tandem, as nutrition and disease are intrinsically linked. 'Among the alternative and sustainable diets that are currently being used, soybean is among the most attractive for fish feeds,' explains Dr Overturf. 'However, its use is limited by anti-nutritional plant compounds that reduce nutrient absorption, due to negative changes in the mucosal lining of the intestine, termed intestinal enteritis. Many aquaculture-related diseases are linked to mucosal changes, and there is also evidence that alteration of the intestinal mucosa may increase disease susceptibility through disturbance of the host's natural microbiome.'

Harnessing Genetic Selection

Central to the team's work has been the establishment of a genetic enhancement program for the selection of rainbow trout fed alternative plant-based diets, focusing on feed conversion, weight gain, evaluation of disease resistance, and development of enteritis. Rainbow trout are a useful model because they are highly domesticated, rapid-growing, and their relatively large size makes them suitable for studies that require large quantities of certain tissues.

In initial experiments, the team monitored the expression of specific genes in different families and strains of fish that were experimentally challenged with different feeds, environmental conditions or pathogenic microbes. Their results showed changes in gene expression correlating with changes in diet, metabolism, growth, strain, or immune response, and this work began to improve the team's understanding of the effects of diet on nutrient utilisation and fish health. This research led to increasingly sophisticated analysis of differential responses and evaluating changes in the intestinal microbiome.

For aquaculture-reared fish, the fillet is the main product sold to consumers. Rather than increasing growth strictly by measuring weight gain, the team knew that it would be of greater commercial benefit to select for a production trait such as efficient muscle growth. Using the information gathered, they set about characterising the expression of genes that control muscle growth, to help them select strains of healthy fish with high-quality lean muscle that would be profitable for producers.

Dr Overturf and his colleagues also evaluated trout for their resistance to diseases, including bacterial cold-water disease and infectious haematopoietic necrosis. They found a significant positive correlation between final bodyweight and resistance to infectious haematopoietic necrosis, and early bodyweight and resistance to bacterial cold-water disease. These results show that at the time of infection, the weight of rainbow trout appears to correlate with survival, indicating a possible link between selecting for growth, while at the same time potentially reducing disease susceptibility. Furthermore, selection for growth and utilisation of plant-based feeds also showed correlations with enhanced non-specific pathogen resistance.

Taking their accumulated body of research into account, it became clear to Dr Overturf and his team that actively selecting rainbow trout for enhanced growth and utilisation of a fishmeal-free diet could have economic benefits in terms of plant-based nutrition, muscle growth, and reduced levels of disease. The team then used genetic selection to breed from those fish that exhibited favourable attributes when fed the

plant-based diet. The result was a single strain of rainbow trout, which exhibited faster growth when fed a fishmeal-free, plant-based diet, without the development of intestinal enteritis. This was the first study whereby a stock of fish had been shown to grow faster and more efficiently when fed an all-plant based feed, compared with a fishmeal-based feed.

Dr Overturf's team also carried out subsequent work to understand how dietary components are interactively processed and trigger molecular, tissue and whole-body responses. They used feeds with varying ratios of protein to fat, and measured the responses in terms of growth, gene expression and protein degradation. 'Our results show that macronutrients are potent regulators of muscle development and growth,' says Dr Overturf. 'This work provides new opportunities to program performance and flesh quality of organisms. The next step is to integrate this quantitative knowledge into application for practical diet formulation and feeding programs.'

Understanding Disease Dynamics

The team has now carried out selective breeding through ten generations of rainbow trout. This has led to the development of a strain of trout that not only does well, but actually thrives, on an all-plant protein diet – growing twice as rapidly as its parental lines.

Interestingly, this strain of trout also shows non-specific disease resistance, and does not develop intestinal inflammation. The selected strain has been shown to have enhanced resistance to bacterial and viral diseases when compared to commercial strains and other trout selected for disease resistance over many generations. The team's work has also revealed a commonality between the expression of a gene in rainbow trout that is implicated in ulcerative colitis and celiac disease in humans. This suggests that rainbow trout selected for plant-diet tolerance could have added utility as a potential biomedical model for human inflammatory bowel diseases.

One negative aspect of plant protein sources, such as soybean meal, is that they can interfere with digestion, causing a diarrhoea-like condition in rainbow trout. The resulting fine faecal particles can adversely affect aquaculture systems and the environment. The prevailing method used to determine faecal particle size requires expensive equipment and is labour intensive. New work carried out by Dr Overturf and his colleague Dr Thomas Welker has focused on developing a visual measurement method that separates faeces into different particle size classes but is also affordable and easy to use.

The team has also found that the addition of guar gum to a soybean diet can significantly improve the amount of large faecal particles – results that were easily detected with the team's new visual classification method. The use of guar gum and other feed binders has the potential to increase the efficiency of waste collection systems in commercial trout aquaculture. Furthermore, the team is refining feed processing methods to increase feed utilisation and improve faeces stability, thereby reducing pollution in hatchery effluent. Improvements in solid waste management can improve animal welfare, reduce negative impacts on the environment, and enable development of aquaculture in a more sustainable way.

The team is currently working on plans to continue their work towards improving our understanding of fish-disease dynamics. Their latest research focuses on multi-disease resistance among trout strains with different genetic backgrounds, and identifying the differing gene responses involved. Dr Overturf believes a unique opportunity exists to develop efficient and economical health maintenance tools for disease in aquaculture.

'The impact of actively improving nonspecific disease resistance against numerous pathogens, both bacterial and viral, through genetic selection would have a tremendous impact in decreasing economic losses to disease,' says Dr Overturf. 'This would also vastly decrease the cost of selection programs that attempt to specifically select individually for multiple problem pathogens.'

The team hopes that their work will be transferable to other fish species, with practical applications across the aquaculture industry as a whole. Farming strains of finfish that thrive on plant-based diets will help to prevent the demand for feed outstripping supply in the face of a growing global population, and allow the industry to develop sustainably.

In addition, the team's work in improving disease resistance and nutrient utilisation could have huge economic impacts. In an industry where 90% of all losses are due to disease and more than half of production costs are related to feed, even single-digit improvements would be significant and could be valued in the millions. Overall, the breadth of this body of work, built up over a 20-year period, has widespread implications for the global aquaculture industry as a whole, with concurrent positive benefits for the environment and human health.

Meet the researcher

Dr Kenneth Overturf
Hagerman Fish Culture Experiment Station
USDA – Agricultural Research Service
Hagerman, ID
USA

Dr Kenneth Overturf gained his PhD in Molecular and Cellular Biology from the University of Nevada-Reno in 1994. After undertaking several research roles, Dr Overturf began working for the USDA's Agricultural Research Service (USDA-ARS) as a Research Geneticist in 2000. He is currently based at the University of Idaho's Hagerman Fish Culture Experiment Station, located in south-central Idaho, near the centre of the US trout industry. For the past 20 years, one of Dr Overturf's main research areas has been utilising genetic selection to improve fish production within the aquaculture industry, focusing on rainbow trout. Dr Overturf has authored more than 80 journal articles and publications in the fields of aquaculture and genetics. He is a respected member of the international aquaculture community, and has made a number of invited national and international presentations on his research.

CONTACT

E: ken.overturf@usda.gov
W: https://www.ars.usda.gov/people-locations/person/?person-id=13501

KEY COLLABORATORS

Dr Thomas Welker, ARS-USDA
Dr Brian Small, University of Idaho
Dr Madison Powell, University of Idaho
Dr Wendy Sealey, US Department of Fish and Wildlife

FUNDING

USDA-ARS
USDA-NIFA: Aquaculture
University of Idaho Aquaculture Research Initiative
Soy Aquaculture Alliance

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RETHINKING STRATEGIES FOR INCREASING SALMON SURVIVAL

It's a long-held belief that a series of dams in the Snake River in Northwest USA constructed nearly 50 years ago has led to serious declines in Chinook salmon populations. However, new research by **Dr David Welch** and his team from Kintama Research Services Ltd shows that survival of Chinook salmon measured by a wide range of government agencies has fallen by 65% along the whole North American West Coast over this period. These results have significant implications for informing conservation strategies to protect and restore this important species.

Salmon Populations in Trouble

The abundance of salmon in the North Pacific has reached record levels. However, most of this increase is in just two species – pink and chum salmon – in far northern regions, attributed in part to ocean ranching – a type of fish farming where juvenile fish reared in hatcheries are released into the ocean to grow before harvest.

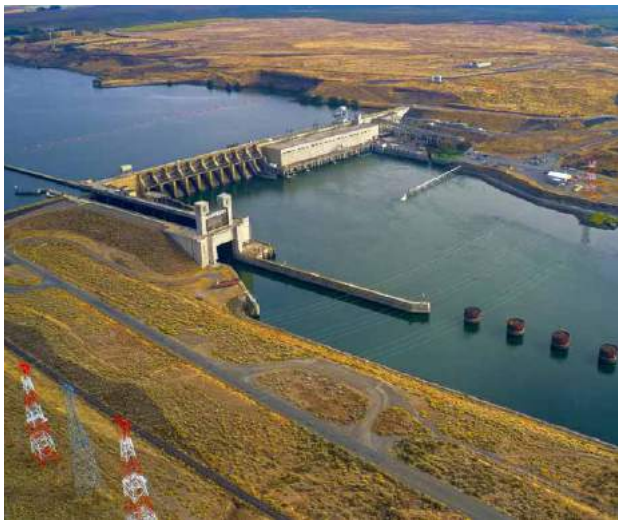
In contrast, all West Coast North American Chinook salmon populations are experiencing serious declines. The situation is similar for most southern populations of coho, sockeye, and steelhead salmon. These dwindling species are of higher economic value and are the focus of many indigenous, sport, and commercial fisheries.

Chinook salmon are native to the North Pacific Ocean and the river systems of western North America, ranging from California to Alaska. They are born in freshwater and can undertake complex movements among a variety of freshwater habitats to find food before migrating to the sea as 'smolts'. They then spend multiple years at sea before returning to their natal freshwater habitat to spawn and die.

In North America, declines in salmon populations since the 1970s were originally assumed to be caused by humans modifying freshwater habitats in the populous southern regions, which initially saw the greatest decrease. On the Snake River, the largest tributary of the Columbia River, many dams have been constructed between its headwaters in the Rocky Mountains to where the Snake joins the Columbia River mainstem. It is widely believed that these dams are a major factor behind population declines in Chinook salmon in the Columbia River Basin. The poor survival of Snake River Chinook salmon has resulted in them being listed under the US Endangered Species Act.

In order to examine the large-scale patterns of Chinook salmon survival from the Snake River and other regions, Dr Welch and his colleagues at Kintama Research Services Ltd have been analysing government data to compare the 'smolt-to-adult return rate' for Chinook salmon from central California to southeast Alaska. The team used the results to examine existing theories around population decreases, and to question whether current management practices are appropriate.

‘We were shocked to discover that the survival of salmon across British Columbia or in Puget Sound is now as low or lower than the reported survival of Snake River populations, which everyone thought had terrible survival because of the dams.’



Challenging Existing Theories

One long-held theory is that the survival of Snake River Chinook is low because poor survival at sea is caused by ‘delayed mortality’. In a nutshell, the theory argues that ocean survival is bad partly because of the many dams the young fish had to migrate through to get there. However, the new data analysis by Dr Welch and his team indicates that Chinook salmon declines are similar from California to Alaska – and most of these river basins have no dams.

‘Our analysis of all the available data shows that survival everywhere is low – and has fallen by three-fold, or 65%, across the board over the last 50 years,’ says Dr Welch. ‘We were shocked to discover that the survival of salmon across British Columbia or in Puget Sound is now as low or lower than the reported survival of Snake River populations. Everyone thought that Snake River populations had terrible survival because of the dams.’

Dr Welch is keen to point out that this doesn’t mean that the dams aren’t causing problems for the salmon; rather, the team’s results suggest that the dams’ influence could be minor and they aren’t a major factor affecting salmon productivity.

‘The existence of this same decline in Chinook returns across essentially all of Alaska and the Canadian portion of the Yukon River, where human-induced freshwater habitat impacts are negligible, is an example of how simple explanations are potentially wrong,’ says Dr Welch. ‘If survival across this vast swathe of relatively pristine territory is severe enough to seriously impact salmon productivity, then there is little hope that modifying freshwater habitat in more southern regions will support a newly productive environment for salmon.’

Another key issue identified by the team was a problem with the Passive Integrated Transponder (PIT) tagging system used to record adult salmon survival in the Columbia River. Many millions of dollars are spent each year on this system and in analysing the data from it. However, when Dr Welch and his team looked closely at the system, they found that the harvest of PIT tagged salmon in the fisheries was unaccounted for and was large and variable. This omission introduces major biases into the many survival studies using PIT tags, which assume that harvest in fisheries is negligible.

In fact, the use of the PIT tagging system for studying salmon survival could be even more problematic. Under the terms of the US-Canada Pacific Salmon Treaty, the coast-wide management of fisheries for Chinook salmon is abundance-based, which means that managers are required to increase harvest when Chinook survival is high and restrict harvest when it is low. As a result, managers are actively modifying harvests in just the right way to obscure any survival fluctuations attributable to the dams. Because biologists seeking to improve survival back to the river work independently of the managers and are not accounting for what happens at sea, they may actually be responding more to imperfections in the harvest management system rather than identifying how the dams really affect survival.

This previously unrecognised limitation of PIT tagging methodology is critical to current management efforts in the Columbia River basin, which largely rely on studies using PIT tags. Fortunately, the Kintama team was able to collate sufficient survival data for Columbia River populations using alternative tagging methodology used elsewhere in the Pacific northwest to allow coastwide survival comparisons to be carried out.

CREDIT: Curtis Smith, Coastal Wilderness Adventures

The Way Forward for Salmon Conservation

'Evidence that Chinook salmon smolt-to-adult returns have decreased to roughly 1% in many regions along the West Coast of North America is both surprising and important,' says Dr Welch. 'These decreases in survival have occurred despite governments' best attempts to increase salmon populations through harvest regulation, construction of hatcheries, and freshwater habitat restoration.'

A major assumption underlying these efforts is that regional factors such as habitat degradation or salmon farms significantly contribute to declining Chinook populations. However, the similar decline across the whole study region suggests a different view is likely. 'At the broadest level, the major implication of our results is that most of the salmon conservation problem is likely determined in the ocean by common processes,' explains Dr Welch. 'Nobody really knows why salmon survival is dropping in the ocean – there is much speculation and some correlation-based analysis, but nothing definitive.'

If this view is correct, then developing a better understanding of the relationship between the ocean-phase of the Chinook salmon lifecycle and population survival rates will be central to successful efforts to restore their populations. This has significant implications for current policies for salmon conservation and management. 'Attempts to improve smolt-to-adult return rates by addressing region-specific issues such as freshwater habitat degradation are unlikely to be successful,' says Dr Welch. 'Given the geographically widespread collapse in survival, the research community needs to reassess several core conservation assumptions.'

In terms of the Snake River populations, the theory of dam-induced delayed mortality still plays an important role in Columbia River salmon management. Another of the Kintama team's current results is of direct interest here, as the broad range of populations they studied showed no consistent evidence that migrating through more dams reduced survival – the hallmark of the delayed mortality theory. Therefore, expensive changes to hydropower operations intended to improve survival may have little impact.

The Kintama team recommends that in future better coordination will be necessary between fisheries managers controlling a wide range of ocean and river fisheries and research biologists working in the Columbia River to improve salmon returns, to ensure that the role of fisheries is incorporated into future analyses and not ignored. However, there is also a critical need to move away from correlation-based studies that compare just a few populations to much broader studies which recognise that the contributing factors may be both complex and beyond our ability to control.

Dr Welch believes that closer attention needs to be directed to how smolt-to-adult return rates are quantified and how salmon rebuilding targets are defined in North America. His team is calling for a systematic review by funding agencies to address consistency and comparability of the smolt-to-adult return rate data generated and to further assess the implications of survival falling to similar levels in most regions of the west coast.

Overall, the policy implications of Chinook salmon survival converging to similar levels nearly everywhere along the west coast of North America are profound. The findings of Dr Welch and his team indicate that current salmon fisheries management and population rebuilding strategies both need to be re-evaluated. This could involve moving away from strategies based on historical theories around human-induced freshwater habitat degradation and looking more towards factors driving population decline in the ocean-phase. The way survival data are collated and interpreted is critically important, as is correctly incorporating the impact of fisheries on salmon survival.

Meet the researchers

Dr David Welch
President and CEO
Kintama Research Services Ltd
Nanaimo, British Columbia
Canada

After gaining his BSc in Biology and Economics from the University of Toronto, Dr David Welch went on to study for a PhD in Oceanography at Dalhousie University, Nova Scotia. He joined the Canadian Department of Fisheries and Oceans in 1985 and was appointed head of the High Seas Salmon Program in 1990. Dr Welch is President and CEO of Kintama Research Services Ltd, a company he founded in 2000 to research and develop the technical infrastructure and array geometries necessary to develop continental-scale acoustic tracking technology. It is intended that this technology will facilitate the efficient tracking of individual marine animals (especially salmon) to measure their survival directly in the ocean. Dr Welch has written more than 300 primary scientific papers and technical reports and received an array of awards for his work contributing to fisheries management and salmon conservation. These include both the *Prix de Distinction* (2007) and *Prix d'Excellence* (2008) from Fisheries & Oceans Canada, the *J. P. Tully Medal* in Oceanography from the Canadian Society for Meteorology & Oceanography (2012), and the *Award of Excellence—Fisheries Management* from the American Fisheries Society (2012).

CONTACT

E: david.welch@kintama.com
W: https://kintama.com/about-kintama/leadership-team/
T: +1 (250) 739-9044

KEY COLLABORATORS

Aswea Porter, MSc
Senior Research Analyst
Kintama Research Services Ltd

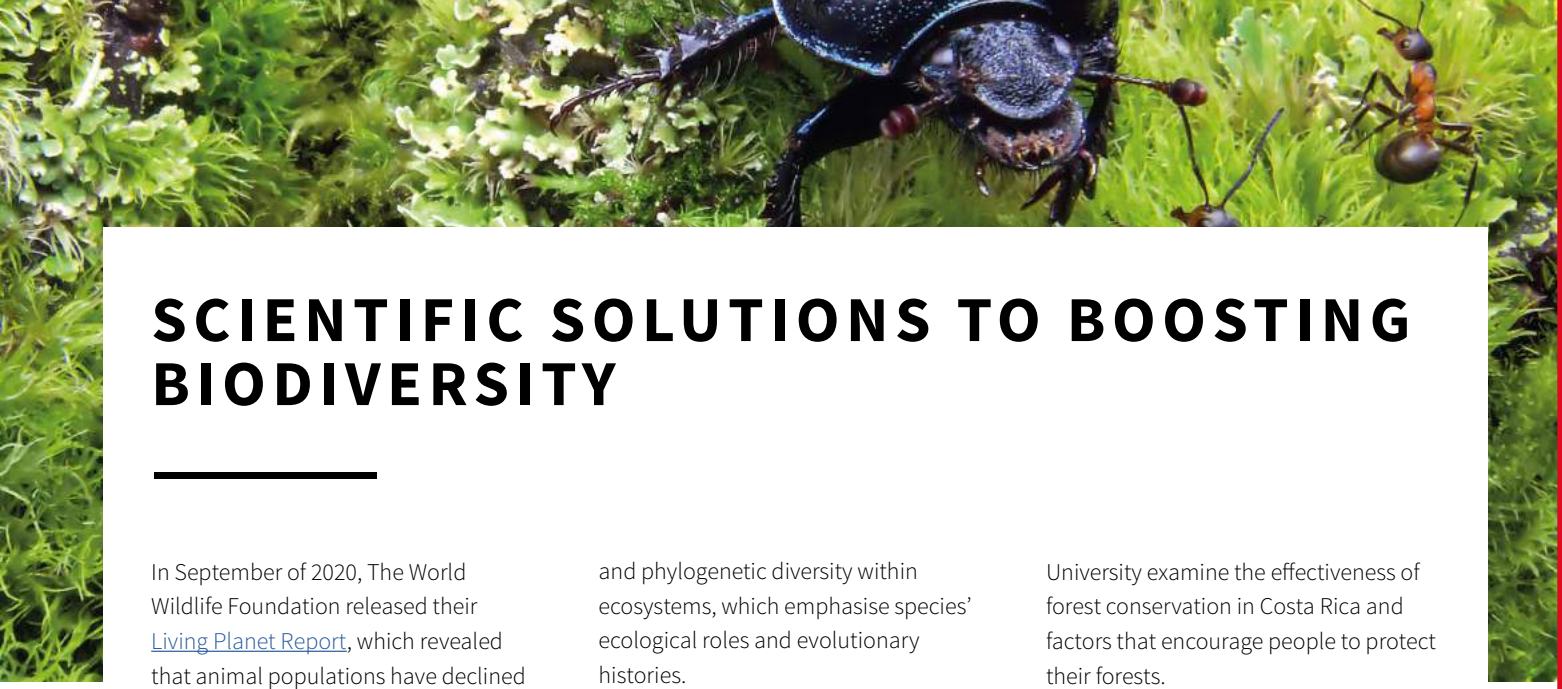
Erin Rechisky, MSc, PhD
Research Manager
Kintama Research Services Ltd

FUNDING FOR THIS PROJECT

Kintama Research Services Ltd
US Department of Energy – Bonneville Power Administration

KINTAMA

ECOLOGY



SCIENTIFIC SOLUTIONS TO BOOSTING BIODIVERSITY

In September of 2020, The World Wildlife Foundation released their Living Planet Report, which revealed that animal populations have declined by a shocking two-thirds since 1970. The document outlines that the environmental destruction behind this catastrophic drop, including deforestation and unsustainable agriculture, also contributes to outbreaks of infectious diseases, such as COVID-19.

Indeed, if we continue to destroy the natural environment, not only will we witness more frequent and extreme wildfires, crop failures, storms, droughts and extinctions, but we will also see more outbreaks like COVID-19, and the next pandemic could be far worse.

Therefore, thousands of researchers across the globe are working to develop solutions that will preserve and restore Earth's natural environments and biodiversity, based on sound scientific evidence. In this section on the edition, we celebrate these research teams, by featuring a selection of promising projects.

Our first featured researcher, Dr Marta Jarzyna at The Ohio State University, has been gaining insight into the mechanisms that give rise to biodiversity patterns. Understanding such mechanisms, which have been rarely explored until know, is imperative to informing effective conservation strategies. Dr Jarzyna's team takes a novel approach to biodiversity monitoring: rather than focusing exclusively on taxonomic diversity, she investigates functional diversity and phylogenetic diversity within ecosystems, which emphasise species' ecological roles and evolutionary histories.

On the topic of evolution, we next meet Dr Paul Wolf of the University of Alabama in Huntsville, who studies the evolutionary histories of ferns, and the relationships between species. By exploring cases of genome doubling and genome downsizing, Dr Wolf hopes to unravel some long-standing mysteries in plant genetics.

Our next four articles focus on forests, particularly their complex ecology and great importance in climate change mitigation. First, we look at the world's boreal (high-latitude) forests, which contain around a quarter of global terrestrial carbon stores – mostly in their soils. Dr Sylvie Quideau and her team from the University of Alberta have been studying the complex interactions involved in the storage and stability of boreal soil carbon. Their work will help to inform management and conservation decisions, with implications for global climate change mitigation.

We then shift our focus to tropical forests, which are some of the most biodiverse ecosystems on the planet. Extensive deforestation has pushed many species found in these forests to the brink of extinction, and conservation efforts have been limited by political and socioeconomic factors within each region. By integrating ecological and social research techniques, Dr Peter Beck at St Edward's University and Dr Michael Wasserman of Indiana University examine the effectiveness of forest conservation in Costa Rica and factors that encourage people to protect their forests.

From Costa Rica, we then jump across the Caribbean Sea to Puerto Rico, where Dr Jess Zimmerman and his colleagues at the University of Puerto Rico are conducting research on the island's forest ecosystems, to provide the basis for future conservation strategies.

Next, we meet a research team from Cornell University, who have developed new protocols for evaluating deer impacts on forest ecosystems in New York State, and the ability of different forest areas to regenerate and retain their biodiversity. Where current methods for managing deer are failing, they consider how data related to deer browsing could provide the rationale for novel methods of reducing deer impacts to retain healthy forests.

Our final article in the edition discusses the alarming decline of pollinating insects, including bees and butterflies. Although there has been a wealth of research conducted into pollinator conservation, private landholders have been slow to adopt practices that support populations of these beneficial insects. Here, we meet Dr Shannon Westlake and Dr Kevin Hunt of Mississippi State University, who have been investigating landholders' attitudes towards such conservation practices and barriers to the adoption of these methods, with the aim of developing targeted support programs to improve the uptake of conservation efforts.

IMPROVING BIODIVERSITY MONITORING TODAY FOR BETTER CONSERVATION TOMORROW

Natural levels of biodiversity support healthy, resilient ecosystems, and thus also support valuable ecosystem services – such as providing clean water. However, pressures from climate change and habitat destruction are altering biodiversity across the globe. Understanding the mechanisms that give rise to biodiversity patterns is imperative to monitoring how it is changing and informing effective conservation strategies. Until recently, these mechanisms have been rarely explored and poorly understood. Dr Marta Jarzyna and her team at The Ohio State University are improving our understanding of biodiversity through extensive research, and developing novel modelling techniques.

Understanding Biodiversity

Human activity has wrought irreversible changes on natural systems across the globe. Climate change – caused by extensive use of fossil fuels and changes in land use – is driving many species to the brink of extinction and altering the habitable ranges of many more. Intensive agricultural practices have a disproportionate effect on insect populations, along with the birds and mammals that rely on them. Natural landscapes converted to farmland and residential or business developments displace many species and cause their populations to dwindle.

'Biodiversity', which describes the natural variety in plant, fungal and animal species within a given habitat, provides a valuable measure of the health of natural systems, because of the functions performed by individual species to keep their ecosystems working optimally. Understanding how biodiversity is changing under human pressures is imperative to informing effective conservation strategies. Additionally, because healthy ecosystems support various ecosystem services – such as agricultural pest control, provision of clean drinking water, and flood mitigation – accurate biodiversity forecasting is important to human societies.

However, despite decades of biodiversity research, no consensus has been reached about the effects and interplay of different processes, the specific ecological and functional attributes of biodiversity, and the scales at which these processes occur. Dr Marta Jarzyna has devoted her research career to illuminating these key interacting factors, developing reliable and accurate characterisations of biodiversity change, and assessing their implications for ecosystems.

Dr Jarzyna and her team in the Jarzyna Lab – part of the Department of Evolution, Ecology and Organismal

Biology at The Ohio State University – tackle four overarching research themes: 1) evidence of biodiversity change; 2) effects of global change on biodiversity; 3) trait-based species and community distributions; and 4) the scale dependence of biodiversity change.

In addition to contributing directly to our understanding of biodiversity across the US and internationally, Dr Jarzyna has also developed novel ecological modelling techniques, which scientists can use to gain deeper, more useful insights in their biodiversity research.

Better Metrics for Better Monitoring

Climate change presents a unique challenge to ecologists and other scientists because of its impacts on natural systems across both space and time. A universal redistribution is being recorded across the globe as species shift their ranges in response to changing climatic zones. The timing of many species' behaviours – such as migration, breeding, and hibernation – is also shifting in response to altering climate patterns.

An accurate characterisation of such temporal and spatial variation in biodiversity is crucial for detecting the influence of human activities and evaluating the implications of biodiversity loss. The quality of biodiversity assessments hinges on our ability to appropriately detect and quantify the species present within an ecological community. Conventionally, these measures have focused on 'taxonomic diversity' – using the traditional definition of species.

However, these measures ignore the evolutionary history and ecological functions of species, and thus, neglect information about ecosystem function and community evolutionary history. A promising alternative involves using biodiversity metrics that include 'phylogenetic diversity', which reflects the evolutionary history of species, and 'functional diversity', which describes the ecological functions of species. This helps researchers to better investigate the processes responsible for the temporal and spatial dynamics of biodiversity.

However, even surveys including all three of these biodiversity 'facets' – taxonomic diversity, phylogenetic diversity and functional diversity – are limited by difficulties in detecting all the species within a given community. Some species may be cryptic and hard to distinguish from similar species without exhaustive molecular studies, others may be particularly shy or elusive, and others may be present in such low numbers as to dramatically reduce the chance of researchers detecting them.

Species detectability may also differ depending on the biodiversity facet used. Therefore, detectability of biodiversity is only rarely constant across space, time, or environments. 'Imperfect detectability of biodiversity will result in erroneous representation of biodiversity change across both space and time,' says Dr Jarzyna, 'ultimately impeding or misleading conservation efforts.'

Accounting for Species Detectability

To address measurement limitations, Dr Jarzyna and her colleague, Dr Walter Jetz from Yale University, developed a rigorous method that accounts for biases introduced through missed species detections based on advanced modelling techniques. Their novel method also has the advantage of being compatible with other modelling and biodiversity techniques.

Demonstrating the efficacy of their approach, Dr Jarzyna and Dr Jetz applied their method to data obtained from the North American Breeding Bird Survey, which included records for around 500 species across five decades, and global records of extinctions. Their goal was to examine the congruency in changes among the three biodiversity facets and their variation across spatial and environmental gradients and scales.

Their analysis demonstrated that all biodiversity facets increased until about 2000, and have since been followed by a slow decline. However, increases in taxonomic diversity were greater than those exhibited by functional and phylogenetic diversity. Community assemblages with a high number of species exhibited smaller changes in functional diversity, and similar patterns

were exhibited towards larger spatial scales. Smaller changes in functional diversity indicate that the corresponding ecosystems may possess some level of functional resilience, through replacement of lost species with others that perform similar ecological functions.

'Gains or apparent stasis at one scale may be fully reconcilable with losses at others, their functional implications will vary by scale and functional component, and both the detection and management of biodiversity change may need to be reconciled with the spatial and temporal scale most relevant to the question,' explains Dr Jarzyna.

The work illustrates the value of measuring multiple facets of biodiversity and accounting for biases introduced by missed species detections. 'Our findings highlight the potential of combining new types of data with novel statistical models to enable a more integrative monitoring and assessment of the multiple facets of biodiversity,' says Dr Jarzyna.

Exploring Functional Trait Resolution

In recent research, Dr Jarzyna and postdoctoral researcher Dr Brooks Kohli have been exploring how the resolution of functional traits can alter the functional structure patterns and causative processes identified during studies of ecological communities, and thus has direct implications for charting the future of biodiversity.

Measurements of functional traits – for example, body size, diet, or breeding behaviours – range from fine-resolution continuous measurements to coarse-resolution binary categories. Despite the knowledge that categorical classification masks functional variability and inflates functional redundancy among species, functional trait resolution has remained critically overlooked.

'Trait resolution often remains beyond the control of investigators, particularly those studying questions at large spatial, temporal, or taxonomic scales, making it essential to understand the implications of trait resolution for detecting ecological processes,' explains Dr Jarzyna.

As demonstrated in her previous research, investigating functional diversity and phylogenetic diversity helps to de-emphasise taxonomic diversity in favour of species' ecological roles, requirements, and evolutionary histories. A trait-based approach also has greater flexibility in investigations, allowing researchers to explore the importance of multiple or opposing processes.

The trait-based approach operates on the assumptions that interactions between species within an ecological community lead to community members with 'divergent' traits – different enough from one another to stably coexist. Meanwhile, if environmental factors are the main drivers behind observed biodiversity the communities should exhibit 'convergent' traits – similar to other community members that need to tolerate the same environmental conditions.

From their preliminary modelling results, Dr Jarzyna and Dr Kohli demonstrated that trait-based tests of interactions between species – measured through divergence of traits – are disproportionately sensitive to trait resolution. They also found that coarser trait resolution may overestimate trait convergence in some systems, leading to erroneous support of environmental factors as the primary drivers behind biodiversity patterns. Therefore, coarse trait resolution introduces pervasive biases into ecological studies.

Addressing the issue of trait resolution bias at its core will require a sustained effort by scientists to identify, collect, and share high-resolution functional trait information across different species and other taxonomic groupings. Ongoing trait databasing efforts aim to facilitate this knowledge collecting and sharing. However, with vast numbers of species to be included, getting anywhere close to completing this effort is a long way off.

In the meantime, simulations like those developed by Dr Jarzyna and Dr Kohli could provide guidance for determining whether a particular ecological investigation may be especially susceptible to trait resolution biases. She recommends that future studies should maximise trait resolution when identifying functional traits for inclusion, but in the absence of fine resolution trait information, this source of bias should be acknowledged and accounted for using measures to mitigate its effects.

Dr Jarzyna concludes, 'By continuing to refine trait-based methods we will improve our understanding of biodiversity and help to create a stronger foundation from which to address and mitigate the biodiversity crisis facing the world.'

Meet the researcher

Dr Marta A. Jarzyna
Department of Evolution, Ecology and Organismal Biology
The Ohio State University
Columbus, OH
USA

Dr Marta A. Jarzyna earned her PhD from Michigan State University, before continuing her postdoctoral research in the Department of Ecology and Evolutionary Biology at Yale University. She currently holds the position of Assistant Professor in the Department of Evolution, Ecology and Organismal Biology and the Translational Data Analytics Institute at The Ohio State University. Research in The Jarzyna Lab focuses on biodiversity and its changes under pressures such as climate change, trait-based ecology and biogeography, and the use of ecological 'big data'. Dr Jarzyna's research has attracted the attention of a wealth of international media and science news outlets, and the larger scientific community. She also devotes time to sharing her knowledge through lectures, seminars and workshops, and has mentored students at every level from undergraduate through to postdoctoral.

CONTACT

E: jarzyna.1@osu.edu
W: http://jarzynalab.com/

KEY COLLABORATORS

Dr Walter Jetz, Department of Ecology and Evolutionary Biology, Yale University
Dr Benjamin Zuckerberg, Department of Forest and Wildlife Ecology, University of Wisconsin-Madison

FUNDING

National Science Foundation
Yale Climate and Energy Institute
Translational Data Analytics Institute, The Ohio State University

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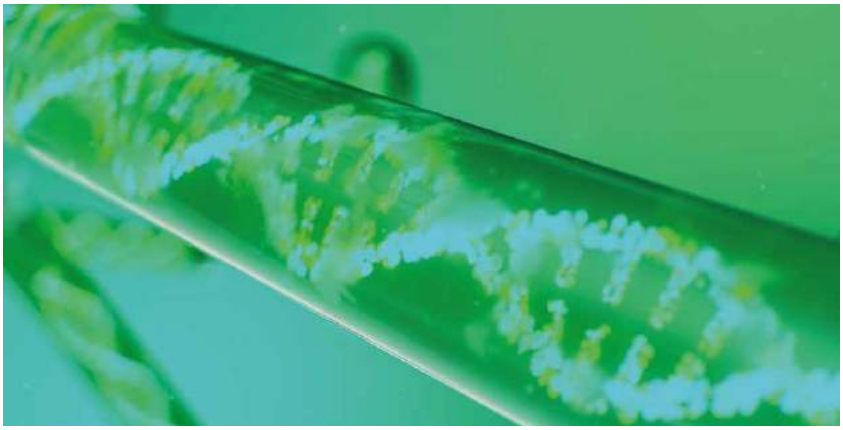
THE OHIO STATE UNIVERSITY

FERN GENOMICS: UNFURLING THE MYSTERY OF PLANT CHROMOSOME NUMBERS

Plants are more tolerant of changes in their chromosome number than animals. Even dramatic changes, such as doubling of the entire genome, sometimes leads to beneficial outcomes. Though a history of genome doubling is common in most plants, the chromosome number in many plants does not reflect this. Complex genome downsizing processes help these plants shed extra genetic information, but are poorly understood. Through comparisons with ferns – a group with high chromosome numbers – **Dr Paul Wolf** from the University of Alabama in Huntsville aims to shed light on genome downsizing.



Plant Reproduction and Evolution

From mountains to the sea floor, plants dominate most of the planet's ecosystems. Over millennia, plants have evolved with a vast array of sizes, shapes, physiologies and reproductive strategies.

Ferns and mosses represent ancient groups of plants, with many characteristics distinct from those that evolved later, such as flowering plants. In particular, the evolution of the seed, which includes a protective layer for the embryo, has allowed more recently evolved plants to thrive in drier habitats. Ferns, by contrast, do not produce seeds, instead relying on two separate and distinct life history phases to achieve reproduction.

In most ferns, large fronds produce spores which disperse to new areas, carried by wind currents. A smaller, but independent, life phase develops from these spores to produce eggs and sperm. In contrast, the egg and sperm-producing life stage has been dramatically reduced to only a few cells within flowering plants.

The spores that different plant groups produce also differ, depending on their evolutionary history. All seed-producing plants and some ferns are 'heterosporous'. In these plants, two types of spores are produced, though they are largely hidden from view. In contrast, the remaining plants, including most ferns, are 'homosporous', meaning that they produce only one type of spore.

Chromosome Number

More than 50 years ago, scientists noted that homosporous plants possess more chromosomes than heterosporous plants. One homosporous fern, *Ophioglossum reticulatum*, has more than 1400 chromosomes – the highest number for any plant, animal, or fungus. For comparison, humans have just 46 chromosomes, grouped into 23 pairs.

Most animals' chromosomes exist in pairs, with each pair comprising two of the same type of chromosome – one from each parent. However, plants are far more tolerant of deviations from this pattern. The number of sets of

chromosomes usually increases through genome doubling during reproduction, where complex processes lead to a phenomenon known as 'polyploidy' in the offspring. For example, this may lead to an organism with a set of four of each type of chromosome – or a 'tetraploid'.

Such 'Whole Genome Duplications' are not uncommon, and are part of the evolutionary history of all plants and probably most animals. Many modern crop species, such as wheat, cotton and potatoes, are polyploid, and polyploidy can be induced artificially to aid the development of new crop varieties. However, polyploidy may also lead to genetic instability and infertility.

Heterosporous plants begin to lose this additional genetic content within a few generations through 'genome downsizing' processes, partially explaining why there is no correlation between chromosome number and genome size in most heterosporous lineages. It is thought that genome downsizing helps to streamline the organism's genetic system by removing chromosomal material that is now redundant. In homosporous ferns, chromosome number and genome size are positively correlated, suggesting that they have fundamentally different, or absent, genome downsizing mechanisms.

Building on three decades of fern research, Dr Paul Wolf from the Department of Biological Sciences at the University of Alabama in Huntsville aims to shed light on these mechanisms through an extensive new research project. Given that homospory is the ancestral condition, Dr Wolf is tackling these problems from a new perspective, by focusing on the question 'Why do heterosporous plants have so few chromosomes?'

Genome Studies of Ferns

Initially, Dr Wolf's research focused on creating a robust framework describing the evolutionary relationships among fern species. To achieve this, he sequenced the DNA contained in the plant cells' chloroplasts, where photosynthesis happens.

However, this genetic information could only provide part of the picture. To understand the full evolutionary complexity of any plant species, researchers must also examine the plant's major genome, which is packaged into chromosomes in the cell nucleus.

Technological advancements in genetic sequencing tools over the last decade have ushered in a new era of fern study. In 2011, Dr Wolf sequenced the more complex genome of a fern-like species for the first time, and in 2018 he published the first genetic sequences for two heterosporous fern species. Currently, Dr Wolf and his collaborators are assembling the first full genome sequence for the homosporous fern *Ceratopteris richardii*.

Polyploidy and Genome Downsizing

Ancient and recent polyploidy has played a large role in the evolution of species. However, its effects are complex. Polyploid lineages include evolutionary dead ends, as well as lineages where the physical effects of polyploidy have led to enhanced survival. Since the extra genetic material is typically unnecessary in polyploids, there is no pressure for the plants to retain it.

In addition to whole genome sequencing of *Ceratopteris richardii*, Dr Wolf and a PhD student in his lab, Sylvia Kinosian, are also investigating genetic and chromosome variation within the whole *Ceratopteris* fern genus. Their hope is that unravelling the evolutionary relationships within this group of species will allow them to identify occurrences of gene duplications and evidence of ancient polyploidy. The researchers have also gathered spores from *Ceratopteris thalictroides*, a natural tetraploid, and are also generating hybrid tetraploid crosses between *Ceratopteris richardii* and *Ceratopteris pteridoides* in their lab.

'Expanding the examination of heterospory and its correlated traits, and studying the effects of genome downsizing, can deepen our understanding of methods of crop improvement.'


CREDIT: Sylvia Kinosian

One advantage of using *Ceratopteris* ferns as the model homosporous plant genus is their rapid lifecycle. Within their lab, Dr Wolf and his team can grow plants through an entire life cycle in as little as 145 days. This gives the researchers an opportunity to conduct multiple experiments as part of their research project in a relatively short period.

Within the next few months, they plan to examine how the chromosomes behave in these ferns during the cellular division that produces spores. This technique allows researchers to see the specially stained chromosomes through a microscope, and investigate how chromosomes are partitioned within the dividing cells. 'This series of experiments will begin to address the question of whether ferns are unable to downsize genomes as rapidly as flowering plants,' says Dr Wolf. However, he notes that additional work on other homosporous plants will be necessary to generalise their findings across the group.

Other Characteristics Associated with Spore Type

Although spore type correlates with chromosome number, other life history characteristics are also associated with homospory versus heterospory. Thus, it remains plausible that other functional traits have a greater influence on the ability to downsize the genome following polyploidy. 'So far, the chromosomal differences between homosporous and heterosporous plants have focused, naturally, on the direct aspects of spore production pattern, especially as this relates to mating systems. However, it is also possible that the correlation is not a function of direct causation,' explains Dr Wolf.

To resolve this, Dr Wolf is examining the life history characteristics of these large groups of plants, and mapping functional traits to spore type. For example, unlike the functionally similar structures in heterosporous plants, the life stage that produces eggs and sperm in homosporous plants is photosynthetic.

Dr Wolf envisages that this work will then feed back into other aspects of the research project, for a more detailed examination of the genes correlated with these traits, and an investigation into gene presence and expression. Previous evidence demonstrates that at least some homosporous plants turn off, or 'silence', extra genes instead of removing them. As such, they may be functionally negating the potentially negative effects of polyploidy.

Implications of this Research

This research represents a novel approach that could address broader biological concepts. 'To date, research on this topic has focused on one or a few plant traits, or by examining genetic attributes of homosporous plants only,' says Dr Wolf. 'This synthesis will bring together data from multiple sources and view the problem from a broader perspective.'

Because many of our crop species are polyploid, a better understanding of the behaviour of chromosomes during reproductive cell division could have general implications for plant breeding. For example, exploitation of natural polyploidy or artificially induced polyploidy is an effective method to introduce beneficial characteristics into crop plant lineages. However, these lineages can be genetically unstable because of the effects of polyploidy on reproductive cell division.

'Thus, expanding the examination of heterospory and its correlated traits, and studying the effects of genome downsizing, can deepen our understanding of methods of crop improvement,' concludes Dr Wolf.

Meet the researcher

Dr Paul G. Wolf
Department of Biological Sciences
University of Alabama in Huntsville
Huntsville, AL
USA

Dr Paul G. Wolf earned his PhD in Botany from Washington State University, before continuing his postdoctoral research at the University of California, Irvine. He then climbed the ranks from Assistant Professor to full Professor at Utah State University, before taking his current position as Professor and Chair of the Department of Biological Sciences at the University of Alabama in Huntsville. Research in his lab focuses on plant evolutionary biology, spanning population genetics to deep phylogeny. During his career, Dr Wolf has published numerous papers in peer-reviewed journals, contributed book chapters, and presented his research at conferences and meetings across the world. In addition to his research activities, he also devotes his time to teaching multiple undergraduate and postgraduate courses, and supervising research students in his lab. Dr Wolf's research predominantly focuses on ferns, however other members of his research team are also researching flowering plants.

CONTACT

W: https://paulwolflab.com/
E: paul.wolf@uah.edu

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

FUNDING

US National Science Foundation

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INVESTIGATING CARBON STORAGE AND STABILITY IN BOREAL FOREST SOILS

The world's boreal, or high latitude forests, contain around 25% of global terrestrial carbon stores – mostly in their soils. These forest ecosystems are particularly vulnerable to climate change, but the effects that rising temperatures could have on their carbon stocks are poorly understood. **Dr Sylvie Quideau** and her team from the University of Alberta have been studying the complex interactions involved in the storage and stability of boreal soil carbon. Their work will help to inform management and conservation decisions, with implications for global climate change mitigation.

An Under-appreciated Carbon Store

Boreal forests are the world's most northerly woodlands – encircling the globe just south of the Arctic. Forming the largest terrestrial community of plants and animals on Earth, boreal forests are characterised mainly by coniferous tree species, and experience freezing temperatures for six to eight months of the year.

These high latitude forests are one of the most vulnerable ecosystems to global warming. While global surface temperatures are projected to rise by 1.8–4°C by 2100, northern regions may experience up to 5°C warming. Such large increases in average temperatures are expected to lead to altered patterns of freeze and thaw, and transformative vegetation shifts in the boreal forest zone.

Boreal forests also represent a huge, but often under-acknowledged, global carbon store. Carbon stocks in boreal forests are estimated at 471 gigatons – close to 25% of the total amount of carbon stored in terrestrial ecosystems worldwide. Boreal forest carbon stocks consist of a complex mixture of carbon pools, with more than 85% of carbon being stored in the soil rather than the vegetation.

Carbon is stored in forest soils primarily in the form of soil organic matter. Organic matter accumulation in soils reflects the influence of several environmental soil forming factors including climate, vegetation and parent geological material. These stores of soil carbon have varying turnover rates along a continuum ranging from days (termed labile carbon), to decades, and centuries (persistent carbon). The different types of carbon pools and timescales over which they cycle make it challenging to predict the response of boreal soil carbon to climate change.

With boreal forest soils representing such large carbon storehouses, any changes in these stocks could significantly affect the global carbon cycle. Yet despite the importance of boreal forest soils to the global carbon budget and their high susceptibility to climate change, very little is known about how warming will affect carbon stocks and dynamics in these soils.

Dr Sylvie Quideau and her team from the University of Alberta are seeking to address this issue, with a research program that investigates how underlying environmental factors control soil carbon storage and stability in boreal forests. 'We're interested in deciphering the pathways leading to the formation of organic matter in boreal soils,' says Dr Quideau. 'We're also looking at how the interactions between soil geological material and vegetation may ultimately determine the response of boreal soil carbon to climatic changes.'

Exploring Forest Soil Carbon Dynamics

To gain a better understanding of the carbon cycle in boreal forest soils, Dr Quideau and her team are exploring the sources, formation pathways and stability of carbon pools at a range of different soil depths within the forest. They have included a variety of boreal forests from across Canada in their research – allowing for characterisation of soil organic matter from a wide range of geological materials, forest stand types and climate.

Their program combines a field-based study of soils in the natural environment, isotope-labelling experiments in controlled-environment chambers, and state-of-the-art analytical protocols. The team is using the latest technological and methodological advances to follow the fate of individual plant molecules through biological communities in the soil, to the soil carbon pools.

Deep soil carbon (below 20 centimetres) represents more than half of the total carbon stored in soils globally. However, less is known about carbon storage in the deep soils of boreal forests than in surface soils, and the mechanisms responsible for its accumulation and persistence are largely unknown.

Dr Quideau's team hypothesises that the parent geological material is the primary driver of differences among soils, and controls the persistence of deep soil carbon. 'Soil carbon age increases with depth,' says Dr Quideau. 'However, deep carbon may not be as stable as originally thought, and new evidence suggests that carbon fluxes in deep soil may be as large as those at the soil surface. We are investigating how soil geological material and the processes leading to soil formation may control the source and stability of carbon present at depth.'

Research carried out so far has led Dr Quideau's team to believe that the carbon pool in surface soil may actually be more chemically stable than deep soil carbon. At low temperatures and in the absence of disturbances, thick forest floors accumulate in boreal forests. Carbon in this layer can be preserved for decades and even centuries in the deeper surface layers. Carbon accumulation in the forest floor varies with vegetation composition, although greater carbon stocks do not necessarily mean greater carbon stability. However, there is an emerging consensus that sensitivity to temperature increases with greater levels of organic matter decomposition or humification.

'Humified forest floors may therefore be more vulnerable to temperature increases than fresh litter,' explains Dr Quideau. 'However, our predictions need to take into account changes in microbial community composition with warming.'

This uncertainty over the impacts of environmental change on microbial communities has led the team to investigate whether vegetation shifts will result in changes to both the composition of soil biological communities and the pathways involved in organic matter breakdown, with consequential implications for carbon persistence. Microorganisms are considered to be the 'eye of the needle' through which most soil carbon passes, so how they are affected by climate

change is critical to the overall soil carbon response.

Another significant carbon store being investigated by Dr Quideau and her team is the root zone, or rhizosphere. This is a unique zone, where the secretion of organic substances by plant roots maintains a continuous supply of 'food' for microbes. This can lead to priming – an increase in surrounding soil carbon decomposition.

'Linkages between plants and microbes are both complex and central to soil functioning,' explains Dr Quideau. 'In order to truly understand the vulnerability of boreal soil carbon to change, these relationships must be explored.' The team is therefore investigating whether soil microbial activity is more sensitive to climate-induced changes in the substances secreted by roots, than to climatic changes themselves. 'These indirect effects of climate change may be more important than direct climatic effects,' says Dr Quideau. 'If our hypotheses are correct, the response of the microbial community to variations in temperature will be greater in the rhizosphere than in the bulk soils.'

Future Management of Boreal Forests

Boreal forests are expected to face large temperature increases in the next century, compared with other ecosystems. Northward migration of the entire boreal ecosystem is predicted, and within the main boreal forest, deciduous trees will replace evergreens. Forest composition will also shift to younger trees due to increased wildfires.

The work of Dr Quideau and her team is therefore critical in evaluating the vulnerability of boreal soil carbon to vegetation shifts, in order to improve prediction of the entire boreal ecosystem response to global climate change. The results will also improve the accuracy of global soil carbon projections in Earth system models, which are currently lacking in their simulations of microbial processes. By incorporating the data and findings from this program, the accuracy of these models should increase significantly.

Dr Quideau's team is also carrying out work exploring the long-term effects of harvest on boreal soils and their carbon storage. Forestry is an important feature of Canada's economy, but there is still considerable uncertainty on how management practices will affect boreal soil carbon storage in the long term. With increasing pressures from a changing climate and intensified forest management, developing better tools and methods for quantifying soil carbon dynamics is of particular importance.

Using remote sensing techniques, the researchers have found differences in carbon retention between harvested and unharvested conifer or deciduous plantations based on site wetness. This work, combined with an improved understanding of the forest soil carbon cycle, is of direct economic importance to the forestry sector. Indeed, the team's findings are beginning to inform and improve sustainable and adaptive management strategies for Canadian boreal forests.

Another distinct, but related area of interest to the team is the impact of invasive earthworms on carbon cycling in boreal soils. Canada's boreal forests had been largely earthworm-free since the Ice Age 10,000 years ago, and evolved in their absence. However, invasive earthworm species, introduced to the continent by European settlers centuries ago, are now making their way into northern boreal forests.

Earthworm activity represents a significant change to forest carbon dynamics, and needs to be incorporated into the overall carbon budget for boreal forests. However, there is a lack of understanding of their long-term impact. The researchers have been quantifying soil carbon stocks and persistence, soil development and microbial communities of invaded and pristine sites of similar soil type and vegetation, in order to improve understanding of earthworm influence on carbon storage.

Preliminary results show a significant reduction of the forest floor associated with an increase in carbon content for the uppermost mineral soil layers. This work also demonstrates the importance of investigating interactive and cumulative effects of multiple disturbances, such as harvesting, forest fires and earthworms, on the carbon balance within boreal forest soils.

Overall, the results of the team's current and future work will provide an unprecedented characterisation of organic matter transformation pathways in boreal forests, which should fundamentally advance our understanding of carbon accumulation and persistence in boreal soils. Dr Quideau believes that these integrated research programs will establish the foundational scientific knowledge required to improve predictions of boreal soil carbon responses to climate change – in turn informing management and adaptation strategies that are tailor-made for sustaining boreal forest ecosystems.

Meet the researcher

Dr Sylvie Quideau
Department of Renewable Resources
Faculty of Agricultural Life and Environmental Sciences
University of Alberta
Edmonton, Alberta
Canada

Dr Sylvie Quideau is a soil biogeochemist with a special interest in carbon fluxes and organic matter processes. After studying for her MSc in Advanced Chemical Technology at the University of Manchester, Dr Quideau gained a PhD in Soil Science from the University of Wisconsin. She is now based at the University of Alberta, where she is a Professor in the Department of Renewable Resources. The focus of Dr Quideau's research is on quantifying the underlying environmental factors controlling organic matter accumulation and distribution in soils, relating measurable organic matter quality indices to ecosystem function and predicating the response of soils to natural and human disturbance. Her research group studies soil organic matter chemistry and biodiversity in Canadian boreal forests. The group is also looking at quantifying carbon and nitrogen fluxes in reclaimed soils, soil carbon retention following land conversion, and the influence of earthworm invasion and fire regimes on forested soils.

CONTACT

E: sylvie.quideau@ualberta.ca
W: https://www.ualberta.ca/agriculture-life-environment-sciences/about-us/contact-us/facultylecturer-directory/sylvie-a-mercier-quideau
W: https://soilbgc.wordpress.com/

KEY COLLABORATORS

Charlotte Norris, Natural Resources Canada
Frédéric Rees, French National Institute for Agriculture, Food, and Environment
Mathew Swallow, Mount Royal University
Justine Lejoly, University of Alberta
Miles Dyck, University of Alberta
Ellen Macdonald, University of Alberta

FUNDING

Natural Sciences and Engineering Research Council of Canada (NSERC)

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SAVING TROPICAL FORESTS THROUGH INTERNATIONAL RESEARCH COLLABORATION

Tropical forests are some of the most biodiverse ecosystems on the planet, but extensive deforestation has pushed many species to the brink of extinction. Conservation efforts have been limited by political and socioeconomic backgrounds of each region. By integrating ecological and social research techniques, **Dr Peter Beck** at St Edward's University, **Dr Michael Wasserman** of Indiana University and their colleagues examine the effectiveness of tropical forest conservation strategies and the factors that encourage people to conserve their forests. Their extensive project also provides international research experience to STEM students from underrepresented backgrounds, and helps foster scientific and cultural exchange between countries.

Precious Ecosystems

Tropical forests are home to at least half of all biodiversity on Earth, including many 'endemic' species – those only found in that region or habitat. These forests also provide valuable ecosystem services, at both local and global scales. For example, with their high year-round productivity, tropical forests help to regulate the climate by capturing and storing atmospheric carbon. They help to purify air and water, while also providing vital resources for local communities.

However, the area occupied by tropical forests has been reduced by half through deforestation over the past fifty years. Vast swathes of forest have been cleared to create cattle ranches or to grow produce such as bananas, palm oil and pineapples. With their natural habitat shrinking, many wildlife populations have also declined, with some becoming extinct.

Primate populations have been particularly affected, with more than half of all species classified as vulnerable or endangered. As well as being some of our closest relatives, non-human primates act as 'ecosystem engineers' by dispersing seeds and altering vegetation. Therefore, the loss of primates from tropical forests has the potential to irreversibly change these habitats. Primate populations occupying degraded habitats are also more likely to become stressed and more susceptible to diseases, and are more likely to be exposed to pollution, such as agricultural pesticides.

Historically, conservation efforts have focused on preserving a portion of the remaining forested areas and species by creating protected areas, such as national parks. However, local communities often rely on natural resources for their livelihoods, and as such, it has become increasingly difficult to create new protected areas. A lack of political support and enforcement has also impacted the effectiveness of these strategies. As a result, policies providing incentives to local communities to preserve the health of forests without the creation of additional protected areas have become more widespread. These alternative strategies, however,

Student researcher Desirée Nieves Canabal in Costa Rica.

Dr Wasserman (left) and Dr Beck (right).

Amy Hall and Meagen Wallace setting an acoustic recorder to monitor bat diversity in Costa Rican forest.

may not be any more effective at conserving tropical forests than protected areas.

Dr Peter Beck, Professor of Environmental Science and Policy at St Edward's University, has been examining the effectiveness of various tropical forest conservation strategies in Costa Rica and Uganda since conducting his dissertation research at Indiana University. Along with his colleague, Dr Michael Wasserman at Indiana University, Dr Beck leads an international research project funded by National Science Foundation's International Research Experience for Students (NSF – IRES) grants.

As part of this initiative, STEM students are trained in ecological and social research methods through independent projects facilitated by Costa Rican hosts at the Organization for Tropical Studies and Osa Conservation. These students, the majority of whom come from groups underrepresented in STEM, are given the opportunity to gain valuable research experience while contributing essential knowledge to improve conservation outcomes.

Investigating Conservation Strategies

Dr Beck and Dr Wasserman successfully devised and implemented the IRES project in Costa Rica, providing international research experience to 16 students, and have recently received IRES funding to continue the project and expand their research to include Panama and Uganda. Rather than serving as research assistants, students design and conduct their own research projects under the guidance of the principle investigators and the foreign hosts.

To collect information on forest conditions and primate populations, students implement a range of field techniques, such as camera traps, air and water quality sampling, and measuring primate hormone levels through faecal sampling. This information provides a measure of the effectiveness of conservation strategies in these areas, revealing the extent that economic incentives and agricultural practices influence conservation outcomes.

Costa Rica, Panama and Uganda are ideal regions for comparisons, because they have significant differences that have caused complications during previous evaluations of conservation strategies. 'By examining similar forests with different conservation incentive policies (Costa Rica and Panama) and different forests with similar conservation incentive policies (Costa Rica and Uganda), we will be able to evaluate the largescale effectiveness of conservation incentive policies, such as payments for ecosystem services and ecotourism, alongside the effects of agricultural practices linked to deforestation, air and water pollution, and biodiversity loss,' explains Dr Beck.

So far, the students' projects have measured the levels of stress hormones in primate faecal samples to investigate the effects of human disturbance, investigated bat distribution and diversity, examined the effects of forest fragmentation by measuring tree size and abundance, surveyed local landowners about agricultural chemical use and conservation practices to assess their impact on local forests, and compared the effectiveness of ecotourism versus direct landowner payments in forest conservation.

In Costa Rica, a portfolio of protected areas, payments for ecosystem services, and ecotourism activities implemented in the 1990s have successfully restored forest cover from around 25% to over 50% by 2011. With the aim of quantifying the effectiveness of each conservation strategy, Dr Beck's and Dr Wasserman's students conducted surveys of private

Project Manager Eric Johnson and student researchers Amanda De La Rosa and Meagen Wallace in OTS laboratory.

landowners to determine their participation in ecotourism and whether they received payments for ecosystem services. Their results indicated that a combination of incentive strategies was the most successful in slowing the rate of deforestation and improving the number of primate species visiting these areas.

By expanding this research to Panama and Uganda, Dr Beck and Dr Wasserman also hope to incorporate evaluations of how socioeconomic factors impact the effectiveness of conservation strategies. The researchers found that wealthier landowners with larger landholdings in Costa Rica were better able to take advantage of ecotourism and payments for ecosystem services.

'As Costa Rica and Panama have much lower levels of deforestation and are significantly wealthier than Uganda, our international comparisons will enable examination of whether level of threat and income level affect the effectiveness of incentive policies,' Dr Beck explains. 'Moreover, Costa Rica and Uganda have implemented payments for ecosystem services, while Panama has not, thus enhancing our examination of the effectiveness of this incentive. Further, although all three countries promote ecotourism and have reserved relatively large amounts of land as protected areas, levels of tourist activity vary across the countries.'

Central Nodes for Collaboration

Collaboration is an imperative part of addressing global environmental problems, such as the largescale deforestation of tropical forests. International arrangements that take advantage of the cultural, infrastructural, educational and economic strengths of each partner help to produce robust research and improved environmental outcomes. However, establishing effective collaborative networks can be a challenging endeavour. Through their IRES project, Dr Beck and Dr Wasserman have demonstrated that research stations can act as 'central nodes' – connecting all participants of the network.

During the initial phase of their IRES projects, researchers at three Costa Rican biological research stations were trained in a variety of ecological and social research methods, including the use of new, advanced equipment. In addition, the IRES funding has helped support the development of a fully functioning endocrinology laboratory for investigating the hormone levels of primates.

Dr Beck, Dr Wasserman and their colleagues demonstrated that participating in social research helped to foster cooperative relationships between field researchers and local communities. 'Collaboration on non-biological topics, such as economic incentives and social networking, has expanded the areas of study of local researchers and enhanced their capabilities to participate in future interdisciplinary projects,' says Dr Beck. Increasing cooperation and collaboration between researchers and the local community may prove to be vital in the efforts to overcome conservation threats outside of protected areas and field stations in tropical forests.

By applying 'social network analysis', which examines the structures and types of interactions between participants in a group, the team illustrated how research stations act as central nodes by connecting governmental agencies, non-governmental organisations, tourists, students and researchers.

These research stations facilitate the establishment of local connections that cannot be achieved by Northern partners in the network directly, such as identifying research sites surrounding the station, negotiating permissions to conduct research at farms in the local community, arranging meetings with landowners and government officials, handling research permits, making reservations, and hiring field assistants or translators. These repeated in-person interactions facilitated by the research stations help to enhance communication and build trust.

The Work Continues

This IRES initiative demonstrates the potential power of collaborative networks to enhance environmental research and conservation outcomes. Additionally, it highlights the importance of multidisciplinary research in addressing global challenges. The incorporation of both ecological and social research techniques allows for a thorough examination of the decision-making trade-offs between payments for ecosystem services, ecotourism, and specific agricultural practices, and how these decisions impact tropical forest and primate conservation.

By continuing their research in Costa Rica and expanding to include Panama and Uganda, Dr Beck, Dr Wasserman and their network of collaborators aim to further untangle the factors contributing to conservation of these precious tropical ecosystems.

Meet the researchers

Dr Peter A. Beck
Department of Environmental Science and Policy
St. Edward's University
Austin, TX
USA

Dr Peter Beck earned a joint PhD in Environmental Policy and Political Science from Indiana University, USA, before continuing his research career at St. Edward's University in Austin, Texas. Here he currently holds the position of Professor and Coordinator of Environmental Science and Policy, where his research and teaching interests lie in policies that integrate environment and development goals, conservation incentives, and campus sustainability.

CONTACT

E: peterab@stedwards.edu
W: https://www.stedwards.edu/directory/employees/peter-beck

Dr Michael D. Wasserman
Department of Anthropology and Human Biology
Indiana University
Bloomington, IN
USA

Dr Michael Wasserman received his PhD from the Department of Environmental Science, Policy, and Management at the University of California, Berkeley, in 2011. He is currently an assistant professor of Anthropology and Human Biology at Indiana University Bloomington, as well as principal investigator of the Primate Environmental Endocrinology Lab (PEEL). His research interests include primate ecology and evolution, environmental endocrinology, nutritional anthropology, evolutionary medicine, and conservation and sustainability.

CONTACT

E: mdwasser@Indiana.edu
W: https://anthropology.indiana.edu/about/faculty/wasserman-michael.html

KEY COLLABORATORS

Dr Rebecca Cole and Rodolfo Quirós, Organization for Tropical Studies, Costa Rica
Dr David Tumusiime, Makerere University Biological Field Station, Uganda

FUNDING

NSF - International Research Experience for Students

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ST. EDWARD'S UNIVERSITY

INDIANA UNIVERSITY

UNDERSTANDING AND CONSERVING PUERTO RICO'S TROPICAL ECOSYSTEMS

Tropical forests and marine ecosystems in the Caribbean are biodiversity hotspots and home to many species found nowhere else on Earth. Increasing environmental stress from a changing climate, such as hurricanes, temperature rises and droughts, threaten to irreparably alter these precious systems. Coupled with ongoing pressures from human activities, some of these areas are especially at risk. **Dr Jess Zimmerman** and his colleagues at the University of Puerto Rico and throughout the US aim to provide the basis for predicting the future of these ecosystems, through their research at the Luquillo Experimental Forest in north-eastern Puerto Rico.

A Biodiversity Hotspot at Risk

The ecosystems of Puerto Rico are home to a vast array of species. Thanks to the country's relative isolation, many species that have evolved here are 'endemic' – found nowhere else on Earth. The coral reefs, seagrass beds, mangrove forests and coastal plains dominating the island's coastal regions give way to wet and dry tropical forests further inland.

In addition to their environmental value, these natural systems provide valuable ecosystem services to Puerto Rico residents, such as fishing and farming opportunities, clean freshwater, and some protection from hurricanes that frequently pass through the area. Thanks to their year-round high productivity, marine ecosystems and tropical forests also help to mitigate climate change by acting as 'carbon sinks' – capturing more atmospheric carbon than they release.

Contrary to previous suggestions, tropical forests are remarkably resilient to environmental stress. However, resilience is not immunity. Puerto Rico's precious ecosystems are at risk from a myriad of factors, with many pressures predicted to increase in the coming decades. For example, climate change is increasing the frequency and intensity of droughts and hurricanes. Rising temperatures contribute to coral bleaching, and may permanently alter the composition of tropical forests.

Protecting these wild spaces, while still accommodating the needs of the human population, requires a thorough understanding of the island's ecology and the long-term impacts of the numerous interacting environmental pressures. Dr Jess Zimmerman from the Department of Environmental Sciences at the University of Puerto Rico and his colleagues in the Luquillo Long-Term Ecological Research (LTER) Program have been exploring how climate change, human activities, hurricanes and other environmental disturbances might be acting together to reduce the health and resilience of tropical ecosystems.

The Luquillo LTER Program, which incorporates the Luquillo Experimental Forest and mountains, and the surrounding urban and coastal areas in north-eastern Puerto Rico, builds on over 100 years of research aimed at informing conservation efforts in the region. Research findings from this forest have fundamentally shaped our understanding of tropical ecosystems, and may help scientists like Dr Zimmerman and his colleagues to more accurately predict potential ecological responses under different climate change scenarios.

Hurricanes: Patterns of Resilience and Vulnerability

The warm air and ocean currents of the tropics generate destructive storms that leave a wake of destruction as they pass over the Caribbean Islands. The variability of hurricanes poses a unique challenge to fully understanding responses of social and ecological systems to environmental disturbance. Hurricanes vary in size, course, wind strength and speed, and cause a range of diverse effects, such as increased wind and rainfall, flooding, and strong currents in coastal areas.

Despite historical assertions that tropical ecosystems are fragile, Puerto Rico's forests and marine ecosystems exhibit clear adaptations that help them withstand and recover from the storms. Even with extensive damage, Luquillo Experimental Forest researchers have discovered that many tree species resist immediate mortality. In addition, tropical ecosystems exhibit remarkable resilience, with some functions and structures returning to their original state relatively quickly. For example, although green leaf litter deposited onto the forest floor causes a nutrient peak in the weeks following a hurricane, soil nutrient cycling and stream chemistry returned to pre-hurricane levels in as little as five years. However, additional stressors, such as rising average temperatures, may hinder the ability of tropical ecosystems to recover from hurricanes.

Historical records also suggest that hurricanes are becoming more frequent. In the period between 1851 to 1990, Category 1 or higher hurricanes, with wind speeds of over 75 miles per hour, passed over the Luquillo mountains every 50 to 60 years. Adding the hurricanes observed until 2017 reduces the return interval to approximately 42 years. Coupled with their increasing intensity, hurricanes may therefore become a more destructive force in future decades. This could drive a shift towards forests dominated by 'pioneer species' – those developing quickly after disturbance events – which suffer higher mortality from hurricane damage than do mature forest species. 'This change in species composition will have cascading effects on streams, biota and biological processes important to ecosystems, such as their ability to store carbon,' says Dr Zimmerman.

His group discovered that a gradient of resistance and resilience exists in north-eastern Puerto Rico, with highest levels on the forested ridges decreasing to towards the marine ecosystems of the coast. In the latter, a history of repeated and accumulating 'anthropogenic' – or human-caused – disturbance, such as increased sedimentation, overfishing and warming sea waters, has left marine systems especially vulnerable to storms.

For example, corals already stressed by increased temperatures may struggle to thrive after extensive structural damage. Native sea grass colonies destroyed or buried during storms may be more likely to be displaced by invasive species. Additionally, because shallow reefs play a critical role in reducing wave energy by up to 97%, degraded reef systems may become more exposed to the damaging effects of hurricanes.

Shifts in community composition are already being documented in some of Puerto Rico's marine ecosystems. 'Chronically declining conditions of coral reef ecosystems due to a combination of cumulative and synergistic anthropogenic and climate change-related impacts are transforming reefs into novel ecosystems, with limited natural ability to recover from disturbances,' Dr Zimmerman explains.

Effects of Climate Change

Global climate models currently predict substantial changes in the rainfall patterns in the tropics, with strong potential for an increase in frequency and intensity of droughts. In 2015, Puerto Rico experienced the most severe drought since 1994, experiencing only 50% of the annual average rainfall. This extreme event provided the LTER researchers with a unique opportunity to build on their previous rainfall exclusion experiments. The reduction in water availability on the island had visible effects on the forest soils and vegetation, and lead to widespread water rationing for residents.

The team recorded a period of high leaf fall early during the drought, coupled with a 30% reduction in the overall growth of trees. Modelling forest productivity under the scenario of steadily increasing drought and temperature revealed that net forest ecosystem productivity could decrease to zero by as early as 2036. Unless forest composition changes or plants acclimate to the drier conditions, this could result in tropical forests switching from carbon sinks to carbon sources, thereby contributing to a positive feedback loop increasing the rate of climate change. Dr Zimmerman and his colleagues were surprised at this result, and are seeking to refine their modelling efforts to further confirm this prediction.

Drought also increases overall greenhouse gas emissions through other processes. For example, soil moisture exerts strong control on greenhouse gas emissions from tropical soils and soil microbial communities, though Dr Zimmerman notes that more research is still required to fully understand these effects. The increased leaf litter accumulates in freshwater systems, which slows the rate of decomposition and thus increases greenhouse gas emissions. The altered conditions of stream ecosystems further inland may also be at risk of incursion by invasive fish species found in water systems closer to the coast.

The temperature increases expected in the next two decades will push many tropical ecosystems into novel temperature regimes. Even small changes in temperature can have seemingly disproportionate effects on tropical plants, which have evolved within a narrow temperature range and thus may be more sensitive to its effects on photosynthesis and respiration. Alarmingly, evidence suggests that tropical canopy trees may already be reaching their upper temperature limit. Beyond this threshold, trees may exhibit a reduced ability to take up atmospheric carbon.

Animals, and particularly 'ectotherms' – which rely on external conditions to maintain their body temperature – may also be sensitive to temperature increases. As with tropical plant species, they have adapted to living in a narrow temperature range, and thus may not have the ability to acclimatise to the new conditions. Some animal species may adjust their ranges to counteract the impacts, for example by migrating further up the mountains; however, many have ranges limited by other factors. The potential loss of species is of particular concern in tropical ecosystems, where a large number of endemic species mean that localised extinction events are often irreversible.

'In the Luquillo Experimental Forest we anticipate three principal changes wrought by a warming world,' says Dr Zimmerman. 'One is the warming itself which may challenge species' physiological tolerances and alter species demography. The other two potential changes accrue to shifts in the disturbance regime caused by increased warming: an increase in the frequency of intense hurricanes driven by the warmed waters of the North Atlantic, and an increase in the frequency or length of dry periods caused by warming, coupled with a change in the seasonality of rainfall.'

Outlook for Tropical Conservation

While their extensive research has already contributed significantly to our understanding of tropical ecosystem responses, Dr Zimmerman and his colleagues have many more questions they wish to answer. In particular, because human and natural systems are tightly linked, they highlight the importance of also examining how environmental changes and hurricanes affect human populations. Our tropical ecosystems are in grave peril, but by providing the basis for better predictive tools and conservation strategies, research from the Luquillo LTER Program may help us to mitigate some of the damaging consequences of a rapidly changing world.

Meet the researcher

Dr Jess K. Zimmerman
Department of Environmental Sciences
University of Puerto Rico
San Juan
Puerto Rico

Dr Jess Zimmerman earned his PhD in Ecology from the University of Utah, before continuing onto postdoctoral research at the Smithsonian Environmental Research Center. He currently holds the positions of Lead Principal Investigator of the Luquillo Long-Term Ecological Research Program, and Professor in the Department of Environmental Sciences at the University of Puerto Rico in San Juan. In addition to his research on tropical ecology in Puerto Rico, Dr Zimmerman has also developed educational tools and programs for school students, teachers, and university students. His work has been published in numerous prestigious publications, and findings from his research have contributed to our fundamental understanding of tropical ecosystems.

CONTACT

E: jesskz@ites.upr.edu
W: http://web.ites.upr.edu/faculty-members/jess-zimmerman

KEY COLLABORATORS

Dr Grizelle Gonzalez, US Forest Service
Dr Edwin A. Hernández-Delgado, University of Puerto Rico
Dr Alonso Ramirez, North Carolina State University
Dr Whendee Silver, University of California, Berkeley
Dr Maria Uriarte, Columbia University
Dr Michael R. Willig, University of Connecticut
Dr Tana E Wood, US Forest Service

FUNDING

National Science Foundation
USDA Forest Service
NOAA Coastal Resiliency Program
University of Puerto Rico
National Fish and Wildlife Foundation

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PROTECTING THE FUTURE HEALTH OF FORESTS IN NEW YORK STATE

The white-tailed deer is an important part of North America's forest ecosystems. However, large deer populations are now causing wide-scale habitat changes and threatening biodiversity, economics, and human health. **Paul Curtis, Kristi Sullivan, Peter Smallidge and Bernd Blossey** from Cornell University have developed new protocols for evaluating deer impacts on forest ecosystems and the ability of different forest areas to regenerate and retain their diversity. Where current methods for managing deer are failing, they consider how data related to deer browsing could provide the rationale for novel methods of reducing deer impacts to retain healthy forests.

The White-tailed Deer

The white-tailed deer is one of New York State's largest mammals, and is an important part of forest ecosystems. Overexploitation and habitat changes resulting from agriculture and forestry practices almost wiped out the state's deer population in the late 1800s. However, conservation efforts in the early 1900s and changes in hunting regulations helped deer herds rebound to a point where their abundance now has devastating consequences for forest plant communities, agriculture, and human health and safety – due to a higher prevalence of tick-borne diseases and deer-vehicle collisions. Furthermore, deer prefer forest edges, so populations now also thrive in suburban areas where lawns and fields are interspersed with forest patches, where fewer hunters and a lack of major predators allow deer populations to grow unchecked.

Gaps in the forest canopy allow light to reach plants on the forest floor, fostering species diversity. However, in many areas, deer browsing has become so intensive that North American forests are losing their previous biodiversity. Deer are selective browsers, and many of the tree species that they prefer to consume are valued for timber, or as food-producing trees for wildlife. Deer also eat wildflowers to a point that previously abundant species, such as orchids, have suffered dramatic population declines and have become rare, threatened, or endangered. The preference of deer for native wildflowers and tree and shrub seedlings also allows invasive plants and invasive earthworms to thrive. Changes in the shrub layer can reduce available food and habitat for other wildlife, including insects, small mammals, and songbirds.

When the variety of species in the forest declines, so does the way that forest ecosystems function. Fewer trees and herbaceous plants can grow to maturity and reproduce. Lack of reproduction or recruitment from juvenile stages (oaks and other trees) associated with high deer browsing may prevent the dispersal of tree and herbaceous species in response to climatic changes. This effect has large ecological and economic consequences for conservation and timber management,

CREDIT: Dr Paul Curtis

and limits potential for climate change mitigation through reforestation.

Landowners, foresters, and conservation and wildlife agencies across New York State are becoming increasingly concerned about deer impacts in their woodlands. However, reliably assessing the size and changes in local deer populations is extremely difficult, time consuming, and expensive. In addition, it typically requires individually marking deer. Also, there is no 'one size fits all'

CREDIT: Martin Feehan

optimum deer density that exists for all areas. The 'right' number of deer a forest can support without substantial damage varies depending on factors including soil fertility, winter severity, and the amount of other food plants available.

To evaluate deer impacts on the state's forest ecosystems, Paul Curtis, Kristi Sullivan, Peter Smallidge and Bernd Blossey from Cornell University and their colleagues have developed two different protocols that use vegetation indicators to assess deer browsing impacts. Evaluating deer impacts by measuring survival and growth of indicator plant species is a good way to assess whether deer populations are too high and threaten both the species and available habitat. These protocols are also useful for measuring the potential of different deer management approaches to reduce these threats.

An AVID Audience

'Any index of deer impacts should respond quickly to changes in the local deer populations and browsing pressure, be based on scientific evidence, and be easily and accurately applied by volunteers in different conditions,' says Dr Smallidge. 'That's why we decided on spring wildflowers and tree seedlings as bioindicators.' Spring wildflowers have been found to respond quickly to changes in deer browsing pressure, and are effective indicators under a variety of conditions. Woody seedlings are available as a measurement tool all year, and have been popular with those interested in tree regeneration.

One of the new methods for rapidly evaluating deer impacts on forest vegetation appropriate for volunteers, foresters, landowners, and others is known as 'AVID': **A**ssessing **V**egetation **I**mpacts from **D**eer. The researchers recruited volunteer landowners and land managers from across the state, running training courses and producing educational materials, to enable them to begin to collecting data on their land. The volunteers collect information by individually tagging and repeatedly measuring tree seedlings that are known to be preferred and non-preferred by deer. In addition, the protocol asks for tagging and measuring certain species of wildflowers broadly distributed and preferred by deer – for example, *Trillium grandiflorum* or *Trillium erectum*, and Indian cucumberoot.

'The focus of this project is on helping local landowners and land managers recognise and understand the changes that are happening on their land – enabling them to play a role in local and state-wide deer management efforts,' says Dr Curtis. Volunteers can enter data online on the AVID website, and through a mobile app developed to provide field portability of the resources developed as part of the project.

Data collected by landowners using the AVID protocol have provided important insights into forest regeneration under the pressure of deer browsing. The team found that the annual average growth of desired tree species, such as maple, ash and oak, is less than one inch (2.5 cm) per year when unprotected from deer. They also found that the average annual height growth of unprotected, less preferred tree species, such as hop-hornbeam and beech that have little utility in the forest industry, may be ten times greater than that of unprotected valuable timber species – reaching more than five inches (12.7 cm) of growth per year.

Standardisation and Legacy Effects

The AVID protocol uses existing plants in forests. However, forests may differ in their tree and herbaceous species composition, even those in close proximity. Decades of high deer abundance have fundamentally changed which species are retained in a forest. This leads to difficulties when foresters, management agencies, or conservation organisations want to assess deer impacts at the landscape level, or compare threats on different parcels of land. Also, in some heavily-impacted forests, including those in suburbia, there may be few native species, creating difficulties in finding enough individuals to tag for repeated measurements.

To provide a common indicator, the team uses repeated plantings of red oak seedlings, or so-called 'sentinels', to evaluate deer impacts on plants, and the efficacy of management practices, including deer fertility control and hunting. They found that oak seedlings protected in cages grew well, but deer ate over 60% of unprotected seedlings each year. They also found that neither sterilisation of female deer, nor recreational hunting, sufficiently reduced browsing rates. Consequently, these techniques were eliminated as appropriate management practices in their study. Instead, they found that allowing volunteer archers to shoot deer in a culling programme resulted in a substantial reduction in the population.

The researchers found that planting oak seedlings as bioindicators was a useful and easy-to-implement protocol to assess deer browsing pressure. However, additional indicator species are needed because browsing rates on more sensitive species of conservation interest, such as trilliums and orchids, may still be excessive, when oak seedlings are not being browsed. The team is currently experimenting with asters and goldenrods to better gauge how deer browsing pressure differs among woody and herbaceous species in the same forest.

A Holistic Approach

Data collected using the AVID protocol is intended to be used to aid in deer management decision-making in New York State. The project team's aim is to achieve a network of AVID participants collecting data from more than 2300 sites by 2024, and they are looking at ways of implementing strategies to incentivise sustained annual monitoring. However, it is also imperative to further assess whether this method alone is sensitive enough to capture changes in deer browsing pressure in response to changes in deer management. AVID, as designed, cannot assess deer legacy effects because the protocol relies on existing individuals. This is where AVID, potentially in combination with the oak sentinel approach, can help to establish what sustainable deer browse levels might look like in different geographic areas. For example, under low-intensity deer browsing, the death rate of oak seedlings is low: 20% over a 6-year period in Wisconsin, and 3% per year in the Appalachian Mountains. However, annual browsing rates of oak seedlings exceeding 10–15% are unlikely to allow this species to regenerate, and oaks need at least a decade to grow tall enough to avoid being eaten by deer.

Acceptable rates of deer browsing for regenerating oak seedlings will likely need to be reduced even further in order to protect more sensitive plant species. 'Wildflowers such as *Trillium grandiflorum* continue to suffer browsing rates that will lead to local extinction, even in areas where browsing rates of oak seedlings fall below 15%,' Dr Blossey says. 'We recognise that using oak sentinels alone will not suffice and that additional indicator species, like those used in the AVID project, will need to be used in assessments once deer populations have declined through control methods.' Therefore, the team is experimenting with additional sentinel plantings and long-term monitoring of individuals to be able to come up with future recommendations to landowners and management agencies.

As is illustrated by the team's research, deer numbers cannot be controlled through fertility control and recreational hunting alone – at least not to the levels required for sustainable forest regeneration and conservation of herbaceous species. Recovery requires substantial reduction in deer herds, but any drastic changes in deer management, such as the introduction of predator species, are likely to be controversial. The researchers believe that their research is now providing the background data required to guide changes in landscape management and forest stewardship. Their work provides an evidence-based approach for making deer management decisions – a potentially emotive subject.

At Cornell University's Arnot Forest, the team is now also working on a new project to examine the potential of novel timber harvesting techniques, which involves the use of logging debris, or slash, to create walls that exclude deer. They plan to evaluate the impact that such techniques could have on regenerating forests, and maximising forest carbon storage. Initial results from the team's experiments using these 'slash walls' are promising, but further research into the dynamics of forest regrowth and carbon sequestration utilising such techniques is needed.

It is clear from the breadth and depth of the team's research that overall, a holistic approach to deer management is necessary to promote forest regeneration in New York State and across the eastern US as a whole. Any such approach should be based on data from initiatives such as the AVID and oak sentinel protocols, and take into account ecological, social, human health, and economic metrics to create a portfolio of indicators that can guide effective decision-making in deer and landscape management. The researchers conclude that: 'The future of our forests, the biodiversity contained in them, climate change mitigation, and human health, are closely linked to our ability to embrace these large-scale changes in deer management.'

Meet the researchers

Department of Natural Resources, Cornell University, Ithaca, NY, USA

Dr Paul Curtis

With a PhD in Zoology from North Carolina State University, Dr Paul Curtis is now a Professor in the Department of Natural Resources at Cornell University. He has coordinated the Wildlife Damage Management Programme at Cornell for the past 30 years, which focuses on reducing conflicts, economic losses and human health and safety concerns caused by wildlife in both rural and suburban landscapes. His work includes wildlife fertility control and population management, community-based wildlife management issues and public education. Dr Curtis is also testing novel methods for reducing wildlife damage to agricultural crops and forest regeneration.

CONTACT

E: pdc1@cornell.edu

W: https://dnr.cals.cornell.edu/people/paul-curtis/

Dr Peter Smallidge

Dr Peter Smallidge holds a PhD from the State University of New York College of Environmental Science and Forestry. He is now based at Cornell University, where he is the NYS Extension Forester and Director of Cornell's Arnot Teaching and Research Forest. Here, Dr Smallidge runs an extension programme called 'ForestConnect', which aims to provide state-wide leadership for educational, research-based programmes that address the stewardship and sustainable production needs of forest management. His overall professional goal is to integrate extension and research in support of productive and healthy forest ecosystems in New York and the Northeastern United States.

CONTACT

E: pjs23@cornell.edu

W: http://blogs.cornell.edu/cceforestconnect/

Dr Bernd Blossey

Dr Blossey holds a PhD in Ecology from The Christian Albrechts University in Germany. He is now an Associate Professor in the Department of Natural Resources at Cornell University. Over the past 30 years, he has implemented biological weed control programs targeting invasive species across North America and studied invasive plant impacts. During the past 15 years, he has focused on assessing impacts of stressors in forest ecosystems, including invasive plants, deer, and introduced earthworms. He is the chair of Cornell University's deer management committee, and has assisted local communities in implementing their own deer management approaches. An important aspect of his work involves developing assessment protocols to gauge effectiveness of management approaches.

CONTACT

E: bb22@cornell.edu

W: http://invasiveplants.net/

Kristi Sullivan

Kristi Sullivan holds a Master of Science degree in Wildlife and Fisheries Science, and is a Certified Wildlife Biologist. She currently works as an Extension Associate in the Department of Natural Resources at Cornell University. She works with private forest landowners, land managers, natural resource professionals, and educators to encourage and support practical approaches for conserving wildlife and biodiversity for current and future generations. Kristi also serves as Director of the New York Master Naturalist volunteer program. To complement her Extension program, her research focuses on developing practical methods for managing and restoring forest habitats, and determining effective means for sustaining and conserving native wildlife in the face of environmental change.

CONTACT

E: kls20@cornell.edu

W: https://dnr.cals.cornell.edu/people/kristi-sullivan/

KEY COLLABORATORS

Tracey Testo, Extension Educator, Agroforestry Resource Centre
Jeremy Hurst, Big Game Program Leader, NYS Department of Environmental Conservation
Michael Ashdown, Research Technician, Cornell University
Jacqueline Frair, Professor, SUNY College of Environmental Science and Forestry
Martin Dovciak, Associate Professor, SUNY College of Environmental Science and Forestry
Andrea Davalos, SUNY Cortland
Jason Boulanger, University of North Dakota
Victoria Nuzzo, Natural Area Consultants
Brett Chedzoy, Cornell Cooperative Extension of Schuyler County

FUNDING

Cornell University Agricultural Experiment Station
Cornell University Cooperative Extension
DoD, Strategic Environmental Research Development Program
NYS Department of Environmental Conservation
USDA-NIFA, Hatch
USDA-NIFA, Smith-Lever

HUMAN ELEMENTS OF POLLINATOR CONSERVATION

The alarming decline of pollinating insects in recent years has garnered a wave of interest from the media, scientists and the public. This has resulted in a wealth of research into pollinator conservation, but despite this, adoption of beneficial practices that support pollinators has been low amongst private landholders. **Dr Shannon Westlake** and **Dr Kevin Hunt** of Mississippi State University have been investigating the human elements behind pollinator conservation, with the aim of developing targeted outreach and support programs to improve the uptake of conservation efforts amongst landholders.

The Importance of Pollinator Conservation

Over the past few years, the decline of insect pollinators has become a prominent topic, gathering much attention and research across the world. And with good reason. Large-scale pollinator loss could spell disaster for some of our most important food crops, and as such, it poses a significant risk to the continued food security of the growing human population.

Loss of suitable habitat, climate change and intensive agricultural practices such as pesticide use have all been implicated in pollinator declines. To conserve and restore pollinator populations, many governmental and non-governmental organisations have used the wealth of recent pollinator research to develop a suite of pollinator 'best management practices' (BMPs) for use on both public and private lands. Many of these pollinator BMPs, such as the use of cover crops and the creation of field margins, have additional benefits to landholders, such as reduced soil erosion and improved soil quality.

Yet despite this, the uptake of pollinator BMPs has been low amongst private landholders. With the majority of the land in the USA owned or rented privately, the adoption of these BMPs amongst private landholders is becoming increasingly important to overall pollinator conservation efforts.

So why have private landholders not become more involved? This pressing question is at the forefront of a recent study conducted by Dr Shannon Westlake and Dr Kevin Hunt at Mississippi State University. These researchers set out to understand the current state of pollinator BMP adoption, attitudes and behaviours of landholders and potential constraints to implementation amongst private landholders in Mississippi, with the goal of developing targeted outreach and support recommendations to increase involvement within this group.

Understanding Attitudes

Although humans are responsible for the threats facing pollinator populations, humans also play an integral role in mitigating and reversing the damage through conservation efforts. Thus, the 'human dimensions' of conservation are an important area of research. 'Put simply, human dimensions research involves studying how people value natural resources, how they want natural resources managed, and how they affect or are affected by natural resources and natural resources management and decision making,' explains Dr Hunt.

‘Put simply, human dimensions research involves studying how people value natural resources, how they want natural resources managed, and how they affect or are affected by natural resources and natural resources management and decision making.’

To determine the attributes that affect landholders’ decisions of whether to adopt pollinator BMPs on their own land, Dr Westlake and her team surveyed Mississippi landholders privately owning or renting over 25 acres of land. The majority of Mississippi land is under private ownership, which reflects the land ownership patterns across the entire USA. However, some of the most important agricultural activities in the area, such as poultry and egg production, forestry and soybean cultivation, do not directly depend on insect pollination. Pollinator BMPs provide additional benefits to the landscape though, and thus, these practices provide value to landholders regardless of whether the primary activity on their land depends on pollinators.

Dr Westlake, Dr Hunt and their colleagues developed a new survey measurement instrument that allowed a thorough investigation of the interrelationships and influence of various attributes on landholders’ intentions to adopt pollinator BMPs. By grouping landholders in different ways, they were able to determine the common attributes driving their intentions to adopt pollinator BMPs. From the approximately 1000 usable responses that the researchers obtained, they found that most of the surveyed landholders had favourable attitudes towards pollinator conservation, with many having adopted at least one pollinator BMP either previously or currently. Many also felt social pressures to implement pollinator BMPs on their own land. However, this highlights the fact that favourable attitudes and social pressure may not be enough to encourage adoption of conservation BMPs.

Perceived constraints, whether in time, skills or resources, was the main attribute influencing the landholders’ intentions to adopt pollinator BMPs in the future. ‘Even if landholders have favourable attitudes and feel social pressure to adopt these pollinator BMPs, they still need to feel like they have the time, resources and skills to actually use them,’ explains Dr Westlake.

Many of the landholders who participated in the study indicated that they lacked adequate knowledge of how to implement pollinator BMPs on their own land, even if they had previously used one or more. ‘This finding may seem surprising because there have been steady increases in messaging and conservation efforts focused on pollinators,’ says Dr Westlake. ‘However, having awareness is not the same as having knowledge.’ Supporting this finding, the landholder groups that were already more involved in implementing pollinator BMPs had greater knowledge and less perceived constraints than the other groups.

Within the ‘land use’ categories, farmers had greater adoption of pollinator BMPs than those who used their land for other purposes, such as timber production, reflecting their greater experience with pollinator BMPs. ‘These results indicate the importance of familiarity with pollinator BMPs for future adoption, as experience with BMPs may allow landholders to feel more confident in their abilities to use them on their properties,’ says Dr Westlake.

Encouraging Greater Involvement

Currently, the messaging surrounding pollinator conservation is broad and non-specific, aiming to be applicable to as many landscapes and properties

as possible. However, while this has raised awareness of pollinator conservation, the lack of specific messaging has left many landholders without the knowledge they need to feel comfortable implementing pollinator BMPs on their own land.

The research team's study reveals that greater knowledge cultivation is necessary to increase future involvement in pollinator conservation. Dr Westlake suggests that to improve the current educational and outreach approaches for pollinator conservation, we need to develop targeted messaging that includes information about pollinator BMP costs, multiple benefits, relative advantages and implementation details. She also recommends that there needs to be more practical workshop opportunities, where landholders can observe demonstration areas, practice skills themselves and connect with others interested in pollinator conservation.

These steps aim to bridge the gap between awareness of pollinator conservation and implementation of pollinator BMPs, by improving familiarity, skills and knowledge amongst private landholders. Targeted education and outreach efforts may help to alleviate the perceived constraints of landholders, leading to increased adoption of pollinator BMPs.

Dr Westlake recommends that greater focus should be given to pollinator BMPs that provide multiple benefits, to create a wider support base across diverse landholders. For example, cover crops that help to prevent soil erosion can also provide nesting and foraging sites for insect pollinators. Increasing pollinator abundance also provides indirect benefits that landholders may find desirable, for example by helping to support the bird populations that use them as a food source. Helping to form knowledge connections like these may help to increase motivation in landholders, as they may feel that practices with multiple benefits have greater value.

Importantly, these suggested steps tap into a basic human need to connect with other people. By bringing together a group of people with a common interest, a great opportunity exists for discussion, sharing ideas and making connections. The sense of community gained from programs such as these help people feel more empowered and connected, and may be an essential component in deepening their commitment to pollinator conservation efforts.

Future Human Dimensions Research

Getting the message to the right people may pose difficulties though. Dr Westlake, Dr Hunt and their colleagues found that the level of disconnect between landholders and sources of information was relatively high. Most landholders indicated that they rarely contacted other people for information about conservation BMPs, and they rarely used BMP publications or were entirely unfamiliar with them.

'This can prove challenging when attempting to share information about BMPs or encourage involvement in outreach workshops,' says Dr Westlake. 'Therefore, we need to work on developing ways to better reach landholders, especially in rural landscapes.' Further examination of communication channels and landholder networks is essential to increasing the reach of targeted conservation messages.

There is still a great deal left to learn about the human dimensions of pollinator conservation, and continuing this research is essential to increasing involvement in conservation efforts, especially amongst private landholders. Additional investigations are key to illuminate further attributes that influence intentions to adopt pollinator BMPs, and improve understanding of how regional differences impact landholder attributes and actions. Studies such as these could also be extended to other groups of people and other conservation efforts.

Although challenges remain and further research is necessary, the results from the team's study indicate that people are interested and ready to engage in pollinator conservation efforts. As Dr Westlake concludes: 'Now is the time to change the role of humans in pollinator conservation from problem to solution.'

Meet the researchers

Dr Shannon M. Westlake
Department of Wildlife, Fisheries and Aquaculture
Mississippi State University
Starkville, MS
USA

Dr Shannon Westlake recently earned her PhD from the College of Forest Resources at Mississippi State University, where she is currently helping champion the university's efforts to become a Bee Campus USA. Her research interests include pollinator conservation, citizen involvement in conservation efforts, and human dimensions, which have been the focus of her graduate research. Specifically, her dissertation focused on attributes affecting private landowner adoption of pollinator best management practices. In addition to her research activities, Dr Westlake has conducted outreach activities with schoolchildren, landowners, and extension professionals to improve their knowledge of pollinator conservation and encourage involvement.

CONTACT

E: shannon.m.westlake@gmail.com

Dr Kevin M. Hunt
Department of Wildlife, Fisheries and Aquaculture
Mississippi State University
Starkville, MS
USA

Dr Kevin Hunt earned his PhD in Wildlife and Fisheries Sciences from Texas A&M University. He is currently a Sharp Distinguished Professor of Human Dimensions, Director of the Human Dimensions Laboratory, and Coordinator of Graduate Studies in the Department of Wildlife, Fisheries and Aquaculture, at Mississippi State University. In addition to his research activities, Dr Hunt also devotes time to teaching undergraduate modules and supervising graduate students. His main research interests include the social and economic aspects of fishing, hunting, wildlife watching, and trapping.

CONTACT

E: kevin.hunt@msstate.edu

KEY COLLABORATORS

Dr Beth Baker, MSU
Dr W. Daryl Jones, MSU
Dr Braden Leap, MSU
Dr Joel Collier, MSU

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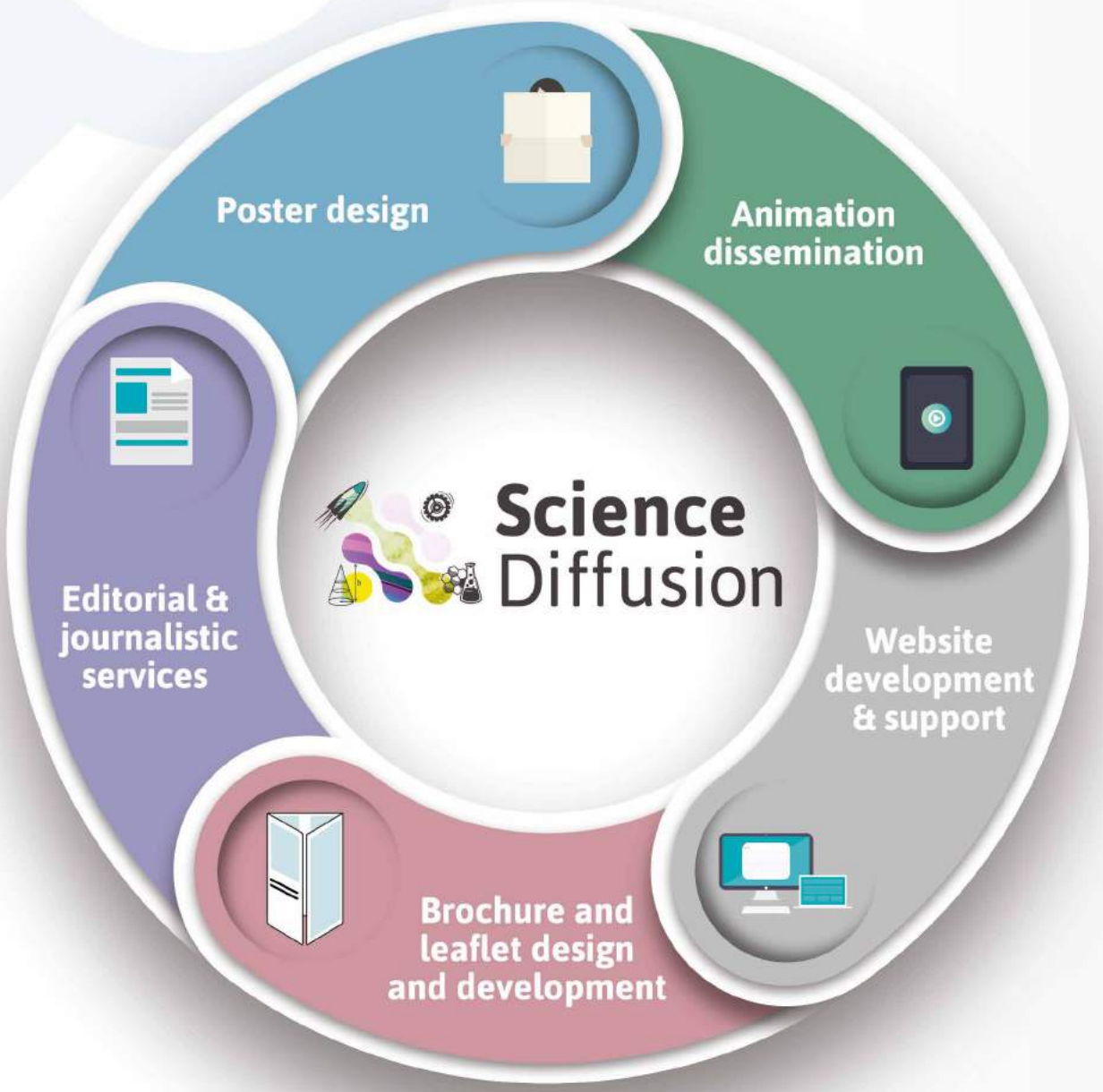

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