THE BACTERIAL PLANT DISEASES PROGRAMME: NARRATIVES OF KNOWLEDGE EXCHANGE, IMPACTS AND IMPACTS-IN-PROGRESS

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INTRODUCTION

Motivation

Consideration of future benefits to stakeholders has been woven into the BPD programme since its beginning. The multiple funders of the programme (UKRI, Defra, Scottish Government) all recognised the critical importance of fundamental research related to gaps in understanding of bacterial plant diseases and at the same time hoped to see ways in which the BPD research contributes to UK agriculture, forestry and the environment. The Coordination Team specialists in stakeholder engagement and impact generation therefore conducted pan-programme activities and also worked with each of the projects individually as 'Critical Friends'.

Critical Friends

In their initial proposals, each project had articulated ways in which it hoped to contribute to 'the real world', while acknowledging that such contributions could take a long time to manifest. Building on these early aspirations, the Critical Friends visited periodically with each project team to encourage critical reflection on and planning for stakeholder engagement and building toward impacts. Early visits facilitated identification of stakeholders for each project and then at the programme level Critical Friends surveyed a range of stakeholders to learn about their interests and how they would like to be kept informed; this was fed back to project teams. Throughout their visits, the Critical Friends encouraged teams to consider steps that they had taken, were taking or could take toward impacts. Visits consisted of good discussions and were usually prefaced by presentations on knowledge exchange and impact generation as processes. In particular, based on published work*, Critical Friend presentations provided five types of impact that could be aimed for and identified. (Conceptual Impacts, Instrumental Impacts, Capacity-building, Enduring Connectivity, Attitude/Culture Change toward knowledge exchange). Presentations also described various factors that could facilitate or hinder generation of impacts, so that researchers could increase their awareness of these variables in their own impact-generating efforts.

To further assist project teams, the Critical Friends produced a guidance document, Impact Generation 'Critical Reflection Aid' for Bacterial Plant Diseases UK Projects (Meagher, Marzano and Paterson). In addition to summarising key points, the document offered several tools with which projects could identify and track early steps toward impacts and consider actions accordingly. These tools were based on the concept of impacts developing over time, so that teams could place their thinking in Early, Mid or Late stages of their project. Project teams were encouraged to use these tools on their own as well as providing a basis for updates when Critical Friends visited.

Programme outreach and communication

In addition, at the programme level, the Coordination Team organised a number of webinars and policy roundtables aimed at stakeholders, providing opportunities for dialogue between them and BPD researchers. Through the CT communications officer, an accessible website, friendly newsletter and social media entries promoted BPD's work to stakeholders; at the programme's end a set of briefing documents provided stakeholders with accessibly summarised findings and recommendations for action.

Shared understanding of knowledge exchange and impacts

With a programme-wide masterclass, and a masterclass targeted at ECRS, the CT specialists expanded upon the impact types, the nature of impact-generating processes such as stakeholder engagement, factors affecting those processes and ways to evaluate impacts. Over time, the BPD community have developed a common mental framework, understanding and language. Confidence increased; for example, at their own meeting in March 2024 programme ECRs indicated that their awareness of and confidence in impact generation (and interdisciplinarity) had basically doubled. Rich activity in this dimension was particularly evident in the concluding BPD conference in March 2024, as projects shared steps taken to promote knowledge exchange with stakeholders and identified a range of early impacts or impacts-in-progress.

A legacy of insights

A set of narratives is provided here to capture – as a snapshot in time – illustrations of good practice in knowledge exchange as well as a range of types of impacts or impacts-in-progress arising from across eight projects. The full-length case studies on Des-BL and BAC-STOP offer diverse impacts/impacts-in-progress, as well as relevant factors in their generation and lessons learned accordingly. Six shorter narratives highlight diverse examples of good practice in knowledge exchange progressing toward impact. As a programme legacy, we hope that sharing these stories will allow other researchers in future to benefit from insights gained during the BPD programme.

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RESEARCH PROJECT: DES-BL

PI/TEAM

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INTRODUCTION

Pectobacterium atrosepticum (Pba) is one of the most economically detrimental bacterial plant pathogens affecting the United Kingdom. Globally, it causes £750M in losses per year. It causes blackleg disease in potato plants, as well as soft rot in tubers. The DeS-BL (Building a Decision Support tool for Potato Blackleg Disease) project has worked toward equipping farmers, agronomists, and policymakers with effective tools for managing this disease and mitigating risks. Work packages include:

1. Unravelling the role of nematodes and insects in disease transmission
2. Investigating the impact of current practices on disease establishment
3. Studying the potato root microbiome and its response to soil conditions, toward biocontrol and management strategies
4. Harnessing data and climate change models for predicting blackleg risk
5. Collaborating with industry and policymakers for implementation and evaluation:

Through the integration of these work packages, the DeS-BL project aimed to provide a comprehensive decision support tool for managing potato blackleg disease. By adopting an interdisciplinary approach and engaging with relevant stakeholders, the team worked to collectively combat this detrimental plant pathogen and safeguard the potato industry in the UK. Integration of these work packages has built a base for development of a comprehensive decision support tool for managing potato blackleg disease.

DESCRIPTION OF RESEARCH ACTIVITY

The Des-BL project oriented each work package toward combatting blackleg disease. Thus, gaining a deeper understanding of the role of nematodes and insects in disease transmission and how that can feed into strategies to mitigate their impact and enhance disease management. Similarly, in order to guide farmers and agronomists towards practices that minimize disease risk, the team investigated the influence of existing agricultural practices, such as irrigation and crop rotation, on disease establishment. Groundwork was laid for potential biocontrol measures by studying the dynamic relationship between the potato root microbiome and its responses to varying soil conditions. On a different level, data from previous disease outbreaks and climate change models led to identification of key drivers of blackleg disease, thus contributing toward a predictive tool for assessing blackleg risk and making pro-active management decisions. Running as an ethos throughout the entire project, the team collaborated with stakeholders to promote evaluation of research outcomes and provision of feedback, in order to ensure the practicality of eventual applications.

IMPACTS

Key stakeholders engaged with the project

- Growers
- Agronomists, groups such as the Agronomy Group
- Potato companies
- Seed Potato Organisation, Scotland
- GB Potatoes
- Potato Processors Association
- CUPGRA (Cambridge University Potato Growers Association)
- Biocontrol businesses
- Policymakers, Regulators

Through regular engagement with stakeholders, the team have achieved the following impacts and impacts-in-progress.

Conceptual Impacts

The team found, and shared, discoveries related to potential vectors, infection mechanisms and biocontrol options for Pba. Stakeholders are becoming more aware of, and indeed keen on, scientific techniques involving bacteriocins (proteins isolated from different *Pectobacterium* species) and potato root exudates that could be screened by breeders for resistance or susceptibility to Pba as having real-world potential to address blackleg disease through novel biocontrol mechanisms and/or breeding for resistance.

Instrumental Impacts

As a key step toward instrumental impacts, the team investigated what form a practical decision support tool on DeS-BL could take, what the uptake could be and any potential barriers to uptake from growers. The project's research generated a platform for development of the decision support tool. The team adopted an ambitious approach in seeking new control options, recognizing that not all attempts would succeed. Several approaches have proved successful, with the potential for additional grants. For example, potato root exudates were identified as correlating with Pba resistant and susceptible varieties, thus holding promise for a quick screening technique that potato breeders could use for sampling, without the need for specialised equipment. Bacteriocins have been identified that can reduce potato infection by Pba, and thus may have potential as a disease control option. From the project, a piece of work from Glasgow University has led to the establishment of a spinout company based on the project's findings; if the company succeeds this will mean that the DeS-BL team has generated a new control method for the disease.

Due to appreciation of the work's importance and credibility, steps have occurred with potential to contribute to longer-term policy impacts; for example, the team has held discussions with policy advisors and Chief Scientific Advisors, as well as contributing to national consultations.

In large part due to recognition of the practical importance of the team's work, which built on extensive previous efforts, the Principal Investigatory (Ian Toth) was awarded the British Potato Industry Award in 2020, given to individuals in the potato industry who have made a significant contribution in their careers. In addition, he has undertaken new roles as Director of the National Potato Innovation Centre (NPIC) and the President of the European Association of Potato Research and is a member of the International Potato Partnership (IPP) - continuing to influence potato research throughout Europe and beyond.

Capacity-building Impacts

The project has conducted workshops and training sessions for practitioners, enhancing their capacity regarding current and future management of black leg disease.

Capacity-building has also occurred within researchers, as the project has offered lessons regarding communication dynamics between researchers and practitioners. Ongoing discussions across various project members have influenced how young scientists (within and even beyond the project) approach their future efforts. For example, a presentation on the project's stakeholder engagement at a conference in Italy prompted young researchers to rethink their approach, realizing the importance of engaging with stakeholders early on.

> *'I gave a talk about the project and the way that specifically it was about how to link with stakeholders and a lot of young people, young researchers from all around the world, came up to me afterwards and said that was interesting because actually there is a tendency for us to decide what needs to be done and then we tell industry or stakeholders what we've done afterwards. But actually engaging with them and finding out what they want you to do is something that they thought was too far away; they didn't really see that link and they didn't know how to contact people.'*

This sort of understanding is likely to have been embedded as an important dimension of their capacity in the next generation researchers involved in the project: 2 PhD students and 7 MSc students.

Enduring Connectivity

The team, within and beyond this project, has worked to convene researchers, industry and government. For example, the project had SASA (Science and Advice for Scottish Agriculture, a division of the Scottish Government's Agriculture and Rural Economy Directorate) as a partner; not only did SASA undertake work on the project but they also came to regular project meetings and retreats to share a government perspective. These gatherings benefited in particular from the fact that Scotland's Chief Plant Health Officer brought advice gained through many years of plant health expertise. Stakeholders have come to appreciate the long-term nature of research in this area. For example, a stakeholder interviewee talked about the ongoing nature of the project in conjunction with expectation of long-term interaction, with researchers and stakeholders sharing a mutual interest in continuing collaboration. Even the current stage of the work is seen as providing useful insights, such as the influence of laboratory findings on the field observations, particularly regarding the spread of bacteria in different soil types and the potential role of lighter soils in increased Blackleg risk. Stakeholders hope for conclusive results in the future to guide their agronomic practices, with one example being their interest in understanding the interaction between cover crops and *Pectobacterium* load. They anticipate more dissemination of findings in the coming years as additional data becomes available; not only can researchers share such data but stakeholders such as the Agronomy Group can serve as a channel for further dissemination. There is an underlying trust that communication between researchers and stakeholders will continue. Indeed, team researchers view the current stage achieved in this complex project as foundational groundwork, necessitating targeted approaches in the future. There is an expectation that they will work closely with growers and agronomists during preparation of grant proposals to enhance research design and align it with insights of stakeholders. Already, among the grants secured by the project team are several relating to stakeholders: BBSRC Impact Accelerator Account; BBSRC Commercial Scoping Grant; CASDU Crop Solutions; and Innovate UK.

Attitude/Culture Change toward Knowledge Exchange

Attributed to the retreats and meetings that DeS-BL has organised and participated in, a shift has been observed wherein university partners – traditionally less engaged with industry stakeholders than the applied research organisation partners – are now taking proactive steps in knowledge exchange. Rather than relying on the project lead to identify stakeholders, academics within the project are independently reaching out to industry partners and this has led to direct collaborations. Examples include academics receiving materials from the industry for experiments, obtaining specific potato varieties, and holding discussions with industry partners. Some stakeholders of this project are involved in a project like this for the first time, finding it fascinating to observe the research progress and witness improvements, acknowledging that such projects often generate more questions than answers.

REASONS FOR IMPACT (RELEVANT IMPACT FACTORS)

Problem-framing

The team's problem framing and research design were effectively influenced by feedback from growers and agronomists. For example, during the initial retreat with stakeholders, when presenting results related to bacteriocin work, the team discussed the expression in *E. coli*, in tobacco plants for crushing, and the potential genetic modification of potatoes to produce bacteriocins. The immediate response from growers and agronomists was a clear dismissal, asserting that such genetic modification of potatoes wouldn't be accepted by people. This interaction illustrates the team's sensitivity to the appropriateness of their research design, with input from stakeholders helping to shape the direction of their work.

Research Management

Individuals from four industry organisations were involved directly in the project and there was also an Advisory Group including industry as well as academic partners. In addition to embedding stakeholders and their feedback, the project took a deliberately interdisciplinary approach, which was seen as crucial. The project involved academic members from eight different academic organisations, institutes and universities. Team members brought a variety of different skills and backgrounds, ranging from microbiologists and bacteriologists to physicists (who helped to develop microscopy for visualisation of dynamics within a biological context). Other backgrounds included plant biologists, molecular biologists specialising in plants, bioinformatics, modellers and economists who modelled certain aspects of the work and worked with the industry to see how likely they are to use some of the outputs from the project and how barriers to uptake could be addressed.

The project's research culture was characterized by close collaboration, with a strong appreciation for the equal contributions of each team member and recognition of diverse skills and interactions. Through structured and inclusive management, the team emphasized unity, considered the post-project period, and fostered integration through regular inter-organizational and interdisciplinary meetings, with regular and inclusive meetings every two to four weeks. As a lesson that could prove useful for other teams facing the well-documented challenges of interdisciplinarity and knowledge exchange, effective communication was identified as key, reinforcing the common goal and maintaining regular connections to ensure successful collaboration despite diverse roles and perspectives. Stakeholders were included in both routine sessions and the project's annual meetings, to ensure ongoing engagement and collaboration. The cohesion extended to planning and strategy discussions for papers and future grant proposals. '*I don't think we have any projects without stakeholder involvement. It's now part of how we work. So those relationships can lead to impact.'*

Inputs

The project's funding has been adequate, though there were funding limitations for two specific tasks, leading to the early departure of two universities from the project. Staff turnover presented challenges, with key individuals leaving, but replacements were found, and collaboration with a former member now abroad remains unofficially intact. Despite these staffing issues, the project persevered. Legacy work from various organizations contributed significantly, compensating for the turnover. Access to equipment and resources progressed, with a microscope successfully built using project funds. While each challenge had an impact, none proved insurmountable.

Despite the expense, the decision to prioritize impact and host substantial events was intentional. The project chose to make a significant impact in the first two years, in part supported by the BPD Communications Team. The first in-person retreat, a workshop with scientific talks, long breaks, and social activities over two days, was crucial for team members and key stakeholders to get to know each other.

The team has secured funding through studentships and other sources to support their work. There has been an ongoing discussion on acquiring additional resources to sustain the project, although the nature of scientific funding poses a challenge, as dependence on UKRI funding can present uncertainties and potential disruptions to ongoing efforts.

The project has benefited from other sorts of inputs beyond financial. Among these are the long history of related work by key researchers, the context of an impact-oriented institute, and connection to other projects and activities through the BPD programme.

Outputs

While publications hold great importance for universities, DeS-BL team members saw knowledge exchange as a primary output; therefore there was a focus on meeting people, sharing ongoing work, and engaging in discussions. Some other outputs are captured below.

Dissemination

The team produced different tailored outputs with the goal of targeting different stakeholders. For example, the team produced flyers summarising information on the disease which was distributed to different people. The team provided updates on a website so that visitors could follow their progress and they created a Twitter account to share project developments. The team reached an important follower database of 250 individuals. The team was active in webinars, with outreach extending to international audiences. By using magazines and newspapers the team communicated with an even wider audience, including the public. They participated in conferences, with a focus on engaging academics and stakeholders relevant to their potato research project. Effective visuals, such as engaging microscopy videos of bacteria infecting plant roots were used not only by team members but also by stakeholder collaborators helping with dissemination.

Engagement

Team members have consistently framed their work in terms of the hope for non-academic impacts, particularly through developing a decision support tool to help change field practices and improve Blackleg control. Given this commitment, engagement with stakeholders was woven from the start into the core of the project and its management. The project held 41 engagement activities, including away days, workshops, national and international events, as well as working with media/magazines. Engagement was sometimes informal, through conversations or small meetings, such as when a researcher met with agronomists to share findings from a paper and seek their expertise on management practices. Some engagement activities were more formal. A significant example of the latter was the away day structured into the project, which brought together growers, agronomists and the research team to share work, knowledge and challenges. For example, when a grower during a retreat revealed that individual losses for high-value seed crops could reach £100,000 without insurance coverage, this enhanced the team's understanding of the real-world implications of the disease for growers. The 'sharing' tone of such meetings underpinned and refreshed ongoing connections. Team researchers felt a sense of optimism that research results could be disseminated quickly and ultimately have a tangible impact.

Users

Enthusiastic stakeholders played various important roles in the project. This included providing practical and down-to-earth perspectives on Blackleg in potatoes, highlighting the importance of the research based on its real-world implications and expressing personal connection to the project. The project's Advisory Group has included key stakeholders who have acted as champions connecting the project to a wider community, as they along with some other stakeholders helped to 'cascade' new understanding outwards. Involved agronomists acted as knowledge intermediaries actively communicating project results, including information on irrigation, seed stock, and the use of nematicides, to the growers. For example, an agronomist stakeholder presented practical aspects alongside the principal investigator presenting scientific content at a CUPGRA Conference. That stakeholder has since shared the presentation with others and participated in a meeting in Scotland, providing input during the PI's overview of the project. Stakeholders provided feedback for experimental design, for example on the best stocks to use for exudate experiments. Other user contributions consisted of sending samples to the research team and contacting them by email or phone when something interesting was noted.

Contextual Factors

The impact of COVID on the project was substantial, causing a delay in face-to-face interactions for about a year due to restrictions. The team acknowledged a delayed start and challenges posed by COVID-19, impacting laboratory access and necessitating online meetings. Surprisingly, the shift to virtual meetings, specifically on Teams, may have facilitated increased participation by busy stakeholders. There is nonetheless a concern about potential reduction in formal engagement with stakeholders once the project funding concludes. As for many other BPD projects, dissolution of the Agriculture and Horticulture Development Board was a contextual concern.

The role of the BPD programme itself was seen as a positive contextual factor.

'One thing that's been useful on the project is the ability to link through to other projects. There are about eight other projects … I feel that this is a big team. … it's the way that science should be done and I really hope in the future that other initiatives are going to be as well-coordinated and bring different projects and different teams together. … And we have the possibility of new projects and new interactions arising from joining various parts of projects together which has been fantastic.'

Project members also appreciated the help of the Communications team and the Impact Critical Friends team in helping them get information out to stakeholders and to think deeply about different types of impacts, including awareness that even impacts that are not a major instrumental impact are important.

> *'Before this project I considered only instrumental impacts to be of value, but the Critical Friends Team made it clear that impacts take many different forms. This has made me realise that all impacts, instrumental or not, have value as we work towards those that will make a real difference to our industry partners.'*

LESSONS LEARNED

Things always take longer than expected, whether it's engagement or science; at project initiation a balance is needed between optimism and caution in tempering ambitions.

It is important to maintain an interesting and engaging narrative for stakeholders, and to genuinely engage them. At the same time, it is important to recognise varying levels of enthusiasm and knowledge about stakeholder engagement among team members, emphasizing the need for patience and collective effort, and providing assistance as needed with contacts or know-how as to bringing people together. Projects lacking regular stakeholder contact should incorporate individuals with expertise in this area or establish an Advisory Group with champions who can facilitate connections. Although genuine engagement happened in the DeS-BL project, people should not just wait for it to happen; it takes effort.

Building relationships is key. Personal interactions, such as meetings and coffee discussions, are needed to convey project objectives, understand stakeholder needs, and cultivate lasting relationships. Establishing clear communication expectations at the outset of the project can enhance collaboration and align the different paces of communication between academia and those in the field. Researchers should just take the time to figure out who their stakeholders are and then get a group of stakeholders that they can rely on and who are well-engaged so that the team can build that relationship. Regular contact and being open to ideas and giving space to discuss their insights is important, rather than having academics just talking to people about what they think should happen because the people out in the world doing it probably know a lot more. Timescales can differ between practitioners and researchers, so quick communication can help. Stakeholder involvement is key, particularly in the form of champions; having a good mix of people, with practical as well as research perspectives can help to keep a project's focus on impact goals. As a project stakeholder observed,

> *'To me, what I found most interesting about this project is having such a mix of individuals who are keen to talk and share and understand what each other is after.'*

RESEARCH PROJECT: BAC-STOP

PI/TEAM

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INTRODUCTION

The BAC-STOP project focused on finding out whether the beetle component of Acute Oak Decline (AOD) is essential to the disease and if there is any potential for halting the transmission of harmful bacteria that cause tissue degradation and disruption of the carbon and water balance in trees contributing to the demise of numerous native oak trees in Great Britain. Oak trees are important to the UK environment, landscape, economy and society; they support biodiversity in woodlands; provide timber and have a cultural significance as an iconic symbol of national identity. The project's aims were to acquire evidence of the drivers and biotic causes of the disease that would pave the way for management trials to safeguard oak trees and ensure their protection for future generations. This was addressed by investigating a combination of factors leading to AOD, in particular the interactions between the microbial and insect components involved, as well as assessing land manager perspectives and social acceptability of management options.

DESCRIPTION OF RESEARCH ACTIVITY

BAC-STOP was a multi-disciplinary and multi-organisational project. Research included laboratory work, field work and social science research. The Work Packages:

1. Examined the behaviour of beetles and their interactions with bacteria to determine their role in AOD.
2. Investigated the effects of drought and nutrient stress on oak tree health, disease development, and the oak microbiome.
3. Analysed the perspectives and beliefs of the general public, forest and tree experts, scientists, and policymakers concerning oak trees.
4. Studied the bacteria responsible for AOD and similar infections in other tree species to gain a better understanding of the range of hosts affected by these pathogens.

A key contribution generated by the project's research was establishing that the degradation of stem tissue characteristic of AOD is caused by not just one factor but rather a combination of bacterial species (particularly *Brenneria goodwinii*), beetles (*Agrilus biguttatus*) and environmental stress. For example, chemical compounds from the beetle larvae speed up bacterial cell multiplication and trigger activity of bacterial disease-causing genes. Disease development is more rapid and severe when trees are under unfavourable environmental conditions (nutrient and water stress). Importantly, social research revealed that action to conserve oaks is widely desired (e.g. by nearly 60% of people surveyed) and land managers are willing to undertake management to protect veteran oaks. BAC-STOP research has led to recommendations that include: training and encouraging the public as well as forest managers to monitor trees and report symptoms (toward national recording of AOD occurrence); monitoring *Agrilus biguttatus* populations and distribution in the UK and testing whether bacterial interaction with other insects also triggers pathogenic bacterial responses; and investigating best management practices to promote health and resilience of oak trees so that the trees are not susceptible to beetle ingress in the first instance.

IMPACTS

Stakeholders

Project stakeholders include:

- the forestry sector, e.g. forest managers and rangers, landowners
- Volunteers: citizen scientists and anyone with an interest in tree health
- NGOs
- Government
- Universities, Historic heritage gardens and parks
- Membership organisations.

Conceptual Impacts

There is ongoing debate regarding the involvement of the *Agrilus* beetle in AOD and whether it is essential or coincidental to the disease. While continuing to explore evidence, there are definite indications of a link between the beetle, the disease, and the expansion of affected areas due to climate change. Changing perspectives have led to a more balanced approach among individuals who were either initially sceptical or overly certain about the beetle's role in AOD. This is a conceptual change where thinking has evolved to emphasize the importance of gathering evidence before drawing conclusions.

An NGO stakeholder has highlighted that the spread of oak decline across their estates, with a significant number of trees dying, is a very real concern. The stakeholder described how the project has enhanced their understanding of oak trees and the complexity of oak decline disease in their parks, with potential for translation into on-the-ground management practices. The involvement of individuals conducting research on the trees, analysing bacterial types and disease progression, has contributed to the stakeholder’s comprehension of the disease's impact on the trees' life cycle. In turn, stakeholder input has contributed by providing locations for experimentation and research, which have been essential in providing evidence.

A government body stakeholder highlighted that increased awareness of AOD and its scientific aspects has enhanced their ability to identify signs of the disease in new areas. Created by BAC-STOP, this knowledge is shared with stakeholders and landowners, fostering greater vigilance and facilitating informed reporting on platforms like Tree Alert. Additionally, the conceptual shift includes a broader understanding beyond an initial association of tree bleeds with diseases such as *Phytophthora*, altering their approach based on BAC-STOP’s research findings.

Instrumental Impacts

Progress has been made toward key instrumental impacts. Some are fairly specific. For example, a team member stated: 'In terms of the instrumental direct impacts of research, what we're trying to develop and we've made quite a good progress with so far is developing ways to improve the monitoring of the Agrilus beetle.'

The biggest instrumental impact is probably the discovery that it is the interaction between beetle larvae and the AOD associated bacteria that causes the bacteria to become pathogenic (i.e. fundamental change in behaviour). This has direct instrumental impacts since it will lead to policy guidance. Other instrumental impacts are broader and closely intertwined with conceptual impacts, or changes in understanding. In saying '*I'm more interested in what I can do to save these trees and help in terms of a practical management',* an NGO and large landowner stakeholder highlighted how the BAC-STOP project has influenced their approach to managing oak trees in a park affected by oak decline disease, reflecting on how a conceptual shift in considering the benefits of maintaining standing deadwood within the park contributed to their practical role in managing trees. A better understanding of the disease's life cycle revealed that felling and removing diseased oaks would be ineffective once the beetles had emerged. The project also informed adjustments in park management, addressing issues such as compaction and shade to maintain tree health. Additionally, the knowledge gained prompted a re-evaluation of species selection for replanting, focusing on resilience to oak decline and climate change.

> *When it first started, we were under pressure to fell and remove some of the oaks in the park because that was thought of as maybe getting rid, trying to get rid of the disease or mitigation. But actually, once we understood the life cycle, … there's no point in felling the trees and removing it because it's already too late – you know, the beetles have come out … That meant that we could actually keep those trees standing and actually, that has a huge other benefit for other invertebrates, so certainly, that's like an instrumental or practicing type element and the fact that compaction and shade … and trying to keep the trees as healthy as possible was another aspect that we learned from the programme and we have tried to do that in the park.''*

In one example of changed practices, the team were called to a site to swab test bleeding oak trees. Confirmation of AOD alarmed the site managers, leading to a field visit where they all discussed feasible options for decision-making, emphasizing the importance of tailoring advice to specific land management objectives. This process established a relationship with the site personnel. Subsequently, the project team reviewed the site's forest management plan and produced a report using information from an interdisciplinary effort in the assessment, incorporating suggestions from entomologists, biogeochemists and hydrologists. This input prompted significant changes in the management approach, highlighting the direct impact and influence of interdisciplinary research on practical practices.

A government stakeholder emphasized that a symptoms guide has proven valuable in enhancing their ability to identify AOD symptoms.

Capacity-building Impacts

Face-to-face event meetings with stakeholders have acted as a gateway for collaboration and provision of training. For example, team members from Forest Research have provided training to members of the public enabling them to look out for specific symptoms and the ability to recognise

AOD, but also to assess tree condition in a structured way so that they are confident with their assessment and the data they produced was useful to the researchers.

> *Experiences during the project have also helped to build capacity in knowledge exchange among researchers. For example, a researcher observed that short symptom guides used by the project were appreciated by stakeholders and went on (with a next-generation researcher) to create similar engagement outputs in another project.*
>
> *'Actually, I've kind of borrowed the idea for my PhD student's project. We are looking for sites now for her project, so I said "Oh, we should put together like a little (leaflet), just one page, front and back, just describing what we're looking for, and then we can ask people to look out for it and they can let us know if they find symptoms of this tree disease. … It's an effective way to engage the public and get your research out there.'*

Enduring Connectivity

Founded on openness and knowledge exchange, the BAC-STOP team have built strong, positive relationships with several stakeholders, allowing the team, for instance to visit and take samples and be a trusted source of knowledge and information and help. As a specific example, a casual conversation with a manager at one location laid the foundation for a fruitful collaboration. The manager's recollection of this minor interaction proved important when the team member later sought permission to sample trees, and eventually resulted in funding for a PhD. The relationship further enabled the researcher to seek permission for additional projects and sampling opportunities. The collaboration has expanded to include contributions such as writing articles for the stakeholder's audience.

As another example of mutual benefit over time, work on soil by BAC-STOP researchers has led to the opening of a new PhD position, offered and funded through a charity/membership organisation, to look at the potential for managing oak trees in parkland by making changes to the soil.

Similarly, from a government stakeholder point of view, participation in BAC-STOP events has facilitated extended engagement with scientists. This increased interaction has enhanced stakeholders' knowledge, allowing for better-informed decisions. The extended engagement has proven beneficial to researchers as well, such as with provision of infected logs for research purposes. This ongoing collaboration creates a platform for sustained, longer-term interactions that contribute meaningfully to both research and management.

Attitude/Culture Change toward Knowledge Exchange

The way in which discovery of new soil bacteria was handled by the project enhanced stakeholder enthusiasm for and interest in research. As they published papers, the researchers named a new bacteria species after the stakeholder site where it was discovered and shared their newfound knowledge with the stakeholder, which then engaged with their audiences through social network sites; they received many positive comments.

Pro-active efforts by the BAC-STOP project in the form of face-to-face expert events and symptoms guides provide an interesting overlap between Conceptual Impacts, Capacity Building and a Cultural change where the value of research has been increasingly recognised. There is increased stakeholder awareness compared to a decade ago of bacterial diseases as substantially important in tree health, along with a culture of researcher/stakeholder interaction, formally and informally (e.g., site visits at the experimental site). Organized site visits offered valuable training opportunities, enhancing awareness of bacterial issues.

For their part, researchers too became more aware of the value of learning through interaction with others, aligning an attitude shift regarding the value of knowledge exchange with building capacity for the way in which they will approach future research. For example, an Early Career Researcher observed:

> *'I've not really had that much experience in engagement of stakeholders prior to this project and I think that the key thing I've learned is that there might not be one answer to a specific project or at least not one opinion on a specific problem. I came into the project working to test a specific hypothesis and we've had stakeholders politely say that they disagree with it, which is fine, you know, as, that's what it's all about really. We're obviously trying to go with an open mind and test a hypothesis whether it's supported or not, so it's good to interact with them and hear these challenges that they face because I think one of the things as well, sometimes, I forget, is whilst I'm doing the lab work in a confined space, they're the ones who are the ones working in the forests … I've learned a lot from working with the stakeholders.'*
>
> *A more experienced researcher cited a long history of engagement, noting a useful shift in how it could be perceived, due to reflections on impacts with the programme's Coordination Team.*
>
> *'We've just done that (stakeholder engagement) because that's what we do but suddenly that's now got a name and that name is called impact so what we set out to do, we would have done that anyway, and have always done it, but now suddenly it's become more formalised and so it's sharpened our focus with it. … It's had a lasting impact on us so in our future project proposals and bids and so on, we would be not only more mindful but we would actively include, and budget … for delivering impact and keeping logs of impact and so on. Understanding and learning about the diversity of impacts has definitely been incredibly beneficial.'*

REASONS FOR IMPACT (RELEVANT IMPACT FACTORS)

Problem-framing

Problem framing played a crucial role in understanding the significance of oak tree decline and the need for research and intervention. Initially, oak trees were not considered as major crop trees by the Forestry Commission. However, private owners of oak trees, experienced economic, environmental and cultural loss and recognized the problem. Additionally, the decline of ancient oak trees highlighted the broader long-term impact of losing trees in their prime. The recognition of oak tree vulnerability and the framing of the problem as a significant threat contributed to increased attention and support for addressing the issue.

Research management

The project had a pro-active attitude to research management, emphasizing an interdisciplinary approach and integration of different sorts of expertise. The project had to have such a team because of the multiple factors affecting oak, with AOD being *"a decline disease … (with) various predisposition drivers"*. Building upon years of research on AOD, different individuals and institutions were actively welcomed to contribute to the project, with collaboration valued. As one example, the group's work in the relatively unpopulated emerging chemical ecology field, has necessitated novel research integrating approaches of molecular biologists and cellular scientists. The project's strategy also placed a priority on early and continuing engagement with stakeholders, such as private landowners.

Unlike previous practices of infrequent annual or semi-annual in-person meetings, the transition to Teams has enabled more frequent, regular, monthly engagements. This has helped foster a cohesive working environment that enabled cross-work package communication, knowledge exchange, and leveraging diverse strengths within the project.

Inputs

Regarding inputs such as funding and staffing, the early days of the project were very difficult due to the impacts of COVID-19 (e.g., lab access restrictions) and the general economy, but the team was lucky with the field work, being able to work outdoors. The availability of beetles was always one of the ''anxiety making' aspects of the project, but the generous donations of material for beetle emergence from landowners and managers enabled the project to go ahead.

Outputs

The project has generated significant understanding, articulated through multiple outputs, as discussed below.

Dissemination

Recognising the importance of reaching different audiences, the project team has produced a variety of different outputs to disseminate its findings, through different media formats and media types. The work has already led to a number of scientific publications, a book chapter and presentations at scientific meetings. In addition, the team produced information leaflets for general audiences, popular publications, blogs, Twitter (now X), a film, contributions to webinars attended by stakeholders and delivery of face-to-face events with stakeholders. Newsletters sent to interest groups provide short updates of research in layman's language.

Engagement

The BAC-STOP project deliberately and pro-actively fostered engagement with stakeholders. As one interviewee observed:

> *'I think other projects I've worked with haven't had quite as close a connection with the stakeholders but with the BAC-STOP one, definitely. There's a lot of it, which is great.'*

The team provided information through a variety of events, which reached stakeholders who attended and then often indirectly their colleagues. Stakeholder interviewees spoke of the usefulness of annual events and updates that provided them with the opportunity to receive and filter information and then cascade it outward, to spread their understanding to others. Some of the events were seminars provided to different organisations upon their request.

Benefits from engagement activities were felt by researchers, as well.

'From those interactions, we gain and we learn and we understand how we can improve ourselves, I think, and our methods of communication, perhaps. … Also, we get a bit of an understanding of what people are a little bit resistant to perhaps, or maybe a bit disbelieving about, but also, we quite often ask those people to supply us with information.'

An example of another sort of engagement was provided by a stakeholder who collaborated with the BAC-STOP team by allowing them to conduct research into the oak trees and bacteria on their organisation's land. This led to enhanced understanding of the life cycle and how the disease affects trees, which was helpful to the stakeholder.

'Initially and mainly, it was through Sandra Denman … Her interpretation of (the research done here) helped us with the management of what we did on the park.'

This stakeholder described the utility of the project's engagement efforts, in contrast to formal scientific publications.

'I was initially talking to the people that came here on site and then the workshop day that was done at Little Snoring, the BAC-STOP Open Day, that was probably the best understanding or best engagement element. … I know there have been scientific papers that have come out on the research and everything but for me … I'm more interested in what I can do in terms of management on the ground. … I almost take it for granted that, "You've done the research and you're doing it as the best knowledge that you can research and come up with and then you propose to management," and that's the element I'm going to engage with most - how I can translate what has been learned from it onto the ground because that's the bit that I am involved in.'

Another type of stakeholder engagement included work with citizen scientists, who would for example report bleeds on trees; BAC-STOP would send test kits and then analyse the samples taken. The team also made efforts to engage with younger audiences (e.g., scout meetings, school demonstrations and input into career choices).

Users

Stakeholder interviewees were pleased to note the varied channels through which they could receive information from the project, including for example journal articles, emails, virtual presentations, and face-to-face meetings. One stakeholder, for instance, applauded the long-term effects of events and bulletins in keeping the issue alive in woodland owners' minds, viewing the ongoing awareness as worth the considerable effort invested by the project in organising outreach activities. Stakeholders have themselves contributed to knowledge exchange in various ways, even beyond providing sites for research, for example sending tree photographs, alerting the team to instances of tree disease, helping with sampling, sharing experiences, providing insights on experimental work and spreading information from the project to their own colleagues. In this way, many served as 'knowledge intermediaries' between the project and other stakeholders.

Contextual Factors

Some project objectives have changed dramatically since the creation of the proposal. Researchers hoped to be out in the field collecting samples, but the impact of the COVID-19 lockdown affected these activities, limiting access to the lab and necessitating external help for wider geographic work. However, even during lockdown, early on the BAC-STOP team created simple leaflets, distributing them in paper and online. This allowed stakeholders to become aware of and interested in the team's efforts, and therefore more engaged with the team, so that, for example, if they were to see a bleeding lesion, they would be motivated to let the team know about it.

LESSONS LEARNED

Project team interviewees offered lessons learned useful their own future projects and for others interested in creating impact.

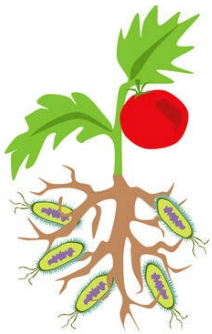
It is important that all team members brainstorm at the inception of the project about: the structuring and the composition of the stakeholder group; how to reach specific groups; how to engage with them right at the beginning of the project; and ways to deliver impacts. Furthermore, as this is a two-way process, it is important to: hear stakeholder views; take on board feedback; and make future changes and updates where needed, including understanding of how stakeholders want to receive information.

A team should learn about all the different ways that knowledge exchange can take place, including webinars, presentations, blogs and leaflets, and how these different routes can target multiple audiences and achieve different impacts. Seemingly casual conversations, often dismissed as impersonal chit-chat, can culminate in valuable opportunities and collaborations. Along with articulating research in straightforward and simple language, researchers should pro-actively embrace opportunities to participate in events, presentations, field trips, and other interactions as these experiences can be transformative, with any initial discomfort diminishing with increased involvement. Rather than fearing a scrutiny of lab work by stakeholders, researchers can find in conversations with stakeholders that general discussions about the research provide an opportunity to convey the project's essence in simple, straightforward language that facilitates a deeper understanding of its impact and enhances their ability to communicate.

As they possess valuable practical knowledge and insights, the project team feel it is crucial for stakeholders to help facilitate the generation of impacts by engaging in open dialogue with scientists. '*(Knowledge Exchange) is a two-way street. …If researchers don't have their participation and understand their needs and how they package information… I think that we're never going to advance. … Stakeholders can get more from things if they are actively involved.'*

> *'A stakeholder would have a lot more knowledge about the actual practical applications of the work … You need to let them ask you the questions and you need to think about that and obviously need to then work together to implement the changes on a bigger scale, so it's about I guess interacting and staying communicative with each other.'*

Disease suppressive microbes and novel growth substrates



Innovative Products from Innovative Science

The problem

Increasingly, crop productivity in glasshouses and polytunnels is being negatively impacted by plant diseases. As current pesticides are becoming ineffective or facing legislative restrictions, there is an urgent need for alternative strategies to control bacterial crop diseases in covered horticultural systems. At the same time, there is an increasing body of evidence suggesting that there are soil-borne microbes that can help plants resist pests and diseases. Selected soils, referred to as 'disease suppressive soils', contain microbes that can form symbiotic associations with plant roots and suppress plant diseases through a combination of mechanisms. The microbes responsible for these health-promoting activities are often absent from soil-free plant growth media (e.g. rockwool), which are widely used for hydroponic cultivation of crops such as tomatoes.

The BPD project on Disease Suppressive Microbes and Novel Growth Substrates aimed to: 1) enhance our understanding of how disease suppressive soils work; 2) create a practical way to utilise disease suppressive microbes from soils to reduce disease in covered horticultural systems; and 3) develop new growth substrates that would improve plant growth and support beneficial microbes. This aimed to provide crucial new methods and insights for the UK and global horticultural industries.

A solution

Biological research by the project team generated a number of important findings, with a focus on interactions between tomato plants and the commercially devastating leaf pathogen *Pseudomonas syringae* pv. tomato, which causes bacterial speck disease in tomato. Researchers examined how different soils changed the capacity of plants to fight off the aboveground disease, investigating how tomato plants can benefit from beneficial bacteria in the soil, through associations with their roots, analogous to humans benefitting from gut bacteria.

Beyond the purely scientific, biological objectives, the team has been committed from the start to develop 'a tractable and commercially applicable model'. To this end, the project team involved expertise from chemists to develop synthetic polyurethane foams that outperformed currently available conventional growing mediums in terms of plant growth, and which could be optimised to better support growth of beneficial bacteria from soils.

Dr Harry Wright, an early career researcher on the project, won the University of Sheffield's Open Research Prize in 2023 for generating open llsource hardware and software (freely available to all) used for developing these synthetic foams. As 'innovation' and 'entrepreneurship' are increasingly cited as important skills for early career researchers, this was timely capacity-building.

Knowledge transfer

The invention process went even further, experimenting with the use of waste foam, such as that from old mattresses, to make the synthetic soil. In 2022, a Knowledge Transfer Partnership grant was awarded to work with a UK company: Vita Cellular Foams (UK) Limited. The company might seem to be an unusual bedfellow for a plant biology project, but the company 'manufactures and converts flexible polyurethane foam for the furniture and bedding industries' – making it an apt partner for further development of this innovative technology.

The project also employed a particularly novel strategy to knowledge transfer by collaborating with artist Anthony Bennett and signwriter Ben PMA to generate multi-media art inspired by the research including digital images, videos and sculpture. This culminated in a display at the Great Yorkshire Show in 2022. In doing so, the project has been able to engage with wider audiences that do not usually interact with such research, enhancing the public's understanding of this important area. This sort of engagement will continue, for example it is planned for the 2024 British Tomato Conference, where the team will interact directly with commercial tomato growers, display artwork, communicate about the research and the importance of microbiomes in combating disease, and showcase their new synthetic foams, exploring how their approaches can be applied to other emerging problems.

Impact steps

In short, the BPD Disease Suppressive Soils project has progressed significantly toward an innovative approach for sustainable, low-input horticultural crop production with greatly decreased need for chemical inputs. Key factors in the invention process have included: a) a project-long vision for, and commitment to, a practical and commercially viable solution; b) research management based on interdisciplinary team efforts including celebration of the work of an early career researcher; and c) partnering with stakeholders – the horticultural industry and a commercial foam manufacturer.

CALIBER

Grappling with Uncertainty in Knowledge Exchange

The problem

Sometimes increasing our knowledge through research leads to a deeper understanding of complexity and, ironically, uncertainty. And - instead of obtaining one simple 'answer' or solution - a multitude of conditional and interlinked answers can be found. Addressing the complex question of differentiating between 'benign infections or damaging epidemics' caused by the bacterium '*Candidatus* Liberibacter solanacearum' (Lso) and its vector insects is one of those instances. The CALIBER project team knowingly took on this question and investigated multiple potential factors in the biology, genetics, environment and agricultural practices in the UK to better understand the threat of Lso to carrot and potato crops. One layer of complexity is our inability to divide the bacterium from its hosts and vectors; and, adding to this, Lso also exists in different variants (called haplotypes) each infecting a different range of plant hosts and each transmitted by different insect vectors, hence posing different risks to UK agriculture. Some of these haplotypes are already present in the UK, as are some vectors able to spread them, yet these are not causing widespread crop damage in carrots or potatoes.

A solution

One of several lines of research in the project has obtained the genomic sequence for specific haplotypes of the bacterium that present different levels of risk to UK agriculture; this information has the potential to be used to develop more finely-tuned diagnostic tests helping to better understand the risks from a detection of Lso. Yet, even this genetic basis is not the whole story. For instance, because bacterium and vector are strongly associated together, changes in farmers' agricultural practices or in landscape scale of plantings, such as choice of non-crops or tree planting for environmental schemes, have the potential to facilitate or hinder the populations of vectors, which in turn increases or reduces the likelihood of the damaging haplotypes to spread and damage crops. Furthermore, of the vectors not currently present in the UK, global trade with associated entry of plant matter plays another large role influencing the risks to the UK from introduction of more damaging haplotypes and other vectors.

Regulatory future

Ideally, in the future, regulatory policy would start taking into account this full picture of complexity and change over time, to 'think of changes in longer-term and at landscape scale'. As a CALIBER team member observed, 'You need to consider that individual changes, for example in plantation practices, could solve one problem but cause another in other systems. The assessment of changes needs to be viewed within the complex landscape in which it takes place rather than as separate from the rest of the landscape.' One way to achieve this is long-term monitoring/assessment and a better consideration of landscape perspective and how a change could modify the risk assessment and contingency plans for new plant diseases, perhaps with policymakers/regulators adding more boxes within a longer-term Risk Assessment.

Communicating complexity

Hoping to raise awareness in stakeholders about the need to balance multiple factors together, even though that makes monitoring, diagnosis and decision-making more challenging, the project team has reflected on 'how do we communicate the complexity to a diverse range of stakeholders, when it is this nuanced?'. Toward that end, the team is taking several steps to share with policymakers, growers and other stakeholders the importance of appreciating multiple interactive dimensions of the situation, now and in the future.

1. They have contracted with a specialist firm to produce an infographic, to communicate their findings in a visually accessible way, within the context of complexity.
2. They hope to develop a tool set or fact sheet, as a workflow approach to testing for different haplotypes with a protocol to see what is currently important.
3. They have individual conversations with Civil Service and other policymakers, toward thinking about how to make practical use of findings, while appreciating complexity.
4. They have been invited participants at a key workshop involving policymakers including individuals from EUPHRESCO, important for European or even wider reach of their findings.

Impact steps

An Instrumental Impact such as fully changing an EPPO protocol could take five years. However, the sound research and communication/relationship-building efforts to date are already building toward Enduring Connectivity and Conceptual Impacts (such as appreciation for complexity and uncertainty over long-term change) that can underpin important regulatory and practice changes.

Future Oak

Gaining Traction for New Concepts

The problem

Increasingly, Acute Oak Decline (AOD) is threatening the survival of UK oak trees; as yet there is not a standard approach to manage the disease. The disease is complex, influenced by multiple factors, including environmental stress and insects as well as pathogenic bacteria.

A solution

The Future Oak project explored a particular dimension of oak trees – their microbiome, or the set of bacteria, fungi and viruses hosted by the trees. The aim was to investigate how some microbes within the microbiome might help to protect against diseases including AOD. Towards this end, the team surveyed microbiomes of 300 oak trees across Britain, in areas where AOD was or was not found; this effectively constructed an 'atlas' of the oak microbiome. Statistical models were built to understand more about environmental factors determining microbial species on trees and the association of each microbial species with disease. Microbial strains were tested for ability to suppress growth of pathogenic bacterial species that are involved in AOD; 341 such strains were isolated. Social science research found that small woodland owners had a general awareness of a tree microbiome and a willingness to use microbial treatments for tree health.

Relevance

The project recommended that microorganisms associated with trees be considered as key to the trees' resilience – and that, in particular, disease-suppressing microorganisms should be explored as potential treatments.

Impact steps

Appreciation of the influence of a 'microbiome' is for many a conceptual shift. The project contributed toward this conceptual impact through not only discussions with small woodland owners but also other forms of outreach. Early on, the project created an animation to facilitate discussion; that has since been viewed numerous times on YouTube, as well as the project and BPD programme websites. In addition to participating in BPD webinars, once Covid allowed, the project also contributed to Forest Research's annual stakeholder event around oak health, with field days and hands-on demonstrations as well as presentations. One project team member highlighted, *'I think, to be honest, that's been the most effective approach, just being able to show an agar plate with some bacteria on it and say, 'These are the bugs that you can't see, that are growing on the leaves of oak trees …. This is what they are and this is what we think they do'.*

Timing has played a part in public awareness and receptivity to the key concepts of the project. With the pandemic occurring as the project began, Covid raised public literacy regarding disease and factors influencing disease spread. Nature and green spaces (including trees) also appear to be more highly valued. Furthermore, current popular media refers frequently to the concept of people's 'gut microbiome', which can include microorganisms with both beneficial and negative resultant effects on the overall human body. Project team members found that the public readily resonated with a comparison of deliberately boosting a healthy oak tree microbiome by using particular bacteria with people using yoghurt as a way to improve their personal gut microbiome and overall health. While of course the comparison cannot be technically accurate in detail, the power of analogy was evident to the team as a tactic to pursue that is accessible to diverse audiences. 'Yoghurt for trees' has gained traction. *'It's difficult to quantify, but I'd like to think that through the animation, the outreach presentations, the workshops and the manager interviews, we've managed to get some of those ways of thinking ingrained now.'*

While it is early days for policymaking, the project PI has contributed toward early steps in policy through participation in a Microbiome Scoping meeting at the House of Lords, set up to advise government by bringing together work on human, animal and plant microbiomes. Evidence from the project helped to reinforce appreciation of the 'microbiome' concept, along with putting on the radar the concept of species within a microbiome acting to benefit (or harm) the resilience of trees. At a Defra meeting, he highlighted the role of microbes in the adaptive capacity and resilience of long-lived trees, again contributing toward eventual integration of the plant microbiome into policymaking considerations.

Ralstonia Phage

Taking Steps toward Scaling Up

The problem

One of the most destructive bacterial plant pathogens, *Ralstonia soanacearum,* causes bacterial wilt globally with a range of agriculturally important plants including potato, tomato, pepper, aubergines and banana. Infections are currently more problematic in warmer temperatures (which may become increasingly relevant for the UK with climate change); but this pathogen already exists in the UK, and, if not monitored, can cause outbreaks of potato brown rot.

A solution

The BPD project has explored the possibility of using bacteriophages, or viruses which kill specific bacteria, as a targeted biocontrol method or 'precision tool' against bacterial wilt. Researchers explored the potential of specific phages to reduce symptoms, decrease abundance of the pathogen and the potential indirect effects on the soil microbiome. To increase awareness and deepen understanding, the team presented their results in several conferences and public speaking events and organised a satellite event on innovative biocontrol of *Ralstonia* for the 12th International Congress of Plant Pathology. They are also writing up a case study for CABI, a periodical read by stakeholders. These actions should contribute toward a conceptual impact regarding the use of bacteriophages for targeted biocontrol of *Ralstonia*.

Expanding geographically

Early research results are promising, so much so that the UK-based project has sparked an emerging international research network to explore possibilities further. Currently, a large consortium bid is being prepared to tackle outbreaks caused by emerging pests, involving companies as well as international partners in Latin America, Africa and China that suffer much more from bacteria wilt-caused plant diseases. Contacts have also been made with the International Potato Center (CIP) to pursue a multi-actor approach putting end-user expertise in the core of the project. In the future, understanding will need to grow regarding different crop species and different geographical and environmental contexts.

Towards scale-up

Along with the scaling up of research, another necessary dynamic for instrumental impact would be the scaling up of treatment methods. The objective is to have companies become capable of large-scale manufacturing and delivery of the phage, ideally in a powdered form. The BPD project team has worked informally and formally with companies on this pragmatic issue. A French company, iMEAN, collaborated in creating a metabolic model of the pathogen and how genetic changes could affect development of disease. The project team worked with the UK company APS Biocontrol on a successful proof of concept - testing the feasibility of spray-drying phages in a powder that could be applied on plants, as well as validating biocontrol efficacy and safety in greenhouse trials. 'This has translational potential. We need to find more money to fully develop the potential. As a proof of concept, it works. We could do a three-year project just for optimisation – that is for the future.'

Impact steps

To date, the project has been conducted within a context in which, in general, 'companies are not yet taking the leap into microbial approaches. They need to see a difference, see the route and how to include it in combination with chemical protocols. That is still emerging, but people are working on it more and more. Opportunities will arise.' With the BPD project, a trajectory has been launched toward a new appreciation and ultimate utilisation of this innovative approach to biocontrol. Key first steps have been taken toward phage products being developed at a commercial level. Multiple steps in research and in further industry collaboration will be needed to investigate feasibility and safety of manufacturing and distributing phage biocontrol at field scale. Beyond this, stakeholder engagement outside the UK will be necessary for the approach to make a difference in diverse settings. 'It will need international engagement to come to fruition'.

The team continues to build an international researcher and stakeholder network, publishing, presenting at conferences, holding conversations with individual stakeholders, sharing its CABI case study and writing an international bid that includes companies and a CGIAR branch in Africa. 'The project has really built something bigger that will build even bigger networks.' Despite their drive toward utility, researchers observe that, as with many if not most research projects, the journey to full instrumental impact will be long, perhaps five to ten years. 'The BPD three-year funding got things started; we need to scale up and continue this important work.'

Pseudomonas – Prunus

Resilience through Enduring Connectivity

The problem

The economically important tree genus *Prunus*, which includes cherries, plums and peaches, can suffer from canker caused by variants of the bacterium *Pseudomonas syringae*. Improved ways for monitoring, early detection and prediction of disease are needed so it is crucial to understand the processes through which *Pseudomonas* bacteria sometimes actually become pathogenic, instead of simply existing within a community of microbes (microbiome) on leaves.

A solution

The BPD project examined the diverse microbiomes of farmed cherry trees and nearby wild plant species, analysing frequency of genes encoding pathogenicity factors, using computational approaches to predict virulence and study composition of *P. Syringae* under different agronomy management practices. In addition, the research investigated transfer of pathogenicity genes between bacteria.

Risks and resilience

An external contextual factor could have caused real problems for the continuity of the work. As for many other research projects within and beyond the BPD programme, the dissolution of the AHDB (Agriculture and Horticulture Development Board) was a shock. The AHDB had for a long time provided crop researchers with both funding and an official channel of communication with stakeholders. However, fortunately for the BPD *Prunus* project and its follow-on activity, robust and long-standing relationships of NIAB at East Malling with stakeholders existed independently of the AHDB. This 'Enduring Connectivity' benefited the project and related research in a time of need, providing resilience and giving rise to a 'good news story':

At the national level, tree fruit growers self-organised to develop a separate panel, with a collective voluntary levy (in the absence of AHDB's levy supporting research and knowledge transfer)

Producers provided voluntary support for demonstrations.

Building resilience

Resilience did not come about by chance. A strong platform had been built over the years in terms of a research culture that promoted engagement with stakeholders.

- The NIAB at East Malling has always taken the approach of connecting to industry; it has become known as 'the' place in the UK for fruit crop research. This allowed the project to build relationships onto the existing network.

- Some relationships are based upon different tree fruit groups (e.g. cherries, apples, plums, pears). In terms of cherry, project researchers at NIAB 'know all the major UK growers'.
- NIAB East Malling uses a Club Model for supporting specific fruit crops, including tree fruit, whereby industry provides funding for supporting demonstration platforms at East Malling to show-case new horticultural techniques.
- Some relationships exist with individual organisations, even sometimes funding from local government to support rural economy, specifically horticulture.

Impact steps

The project team pro-actively built upon this platform. Activities conducted with industry-wide audiences included participation in:

- The annual Fruit Focus event for general fruit industry, held each summer at East Malling
- National Fruit Show, held in Kent for a wide audience, including the general public (In 2022, the team gave several talks on cherry canker, for example)
- The annual Tree Fruit Day, organised by NIAB to disseminate new research (recently the team presented a talk on this cherry research).
- Writing for targeted channels, e.g. Fruit Growers.

Fundamentally, engaging with stakeholders is part of the organisational culture at NIAB. (There was no need for an Attitude/Culture Change impact of increased belief in knowledge exchange!) Informal conversations between researchers and stakeholders are a natural part of their day-to-day work. 'We do those all the time; we don't even think of those as a 'channel' with a formal impact. It is normal for us.' While for these researchers stakeholder engagement has been embedded historically at the organisational level, researchers at other sorts of institutions could also benefit in the long term from building and maintaining close contact and interactive relationships.

Going forward, these relationships, knowledge exchange mechanisms and informal conversations will help researchers explore with stakeholders potential instrumental impacts such as changes in practice which could help to mitigate disease, for example improved monitoring of the extremely diverse and constantly changing cherry microbiome, and preventative cultivation techniques such as use of poly-tunnels and nitrogen fertilisation. Enduring Connectivity will continue to make a difference.

Xanthomonas Threats

Building awareness of the utility of research: bacterial genomes, risk assessment and identification of plant resistance

The problem

Xanthomonas bacteria are very diverse; this genus includes bacteria that can cause disease in over 350 plant species, many of which are crop species. One example is black rot of brassicas, caused by *X. campestris* pv. *campestris* (Xcc), one of the most significant diseases in a range of crops in the UK and abroad, including cabbage, kale, cauliflower, swede, turnips and some ornamental plants like wallflowers. Other *Xanthomonas* species may well become more of a threat to various crops as plant imports increase and effects of climate change can contribute to higher bacterial disease development and spread.

A solution

Given the need for baseline understanding, the project took a stage-appropriate tactic toward the problem of *Xanthomonas* by conducting molecular biology research. Key strands of this research included: the use of whole-genome sequencing to analyse multiple isolates of *Xanthomonas* and to study the relationships between them. Realistically, given the global nature of plant movement, the team also made a point of analysing isolates from many countries around the world and obtaining more isolates to add to their existing collections (e.g. from USA, Argentina, Brazil, Italy, Spain and Portugal). Another strand of research involved screening some species (primarily *Brassica* but also strawberry and popular maize varieties) for resistance.

Relevance of seemingly basic research

Although cutting-edge genomic techniques might seem far from the coalface (or farmer's field), in reality this work has created building blocks upon which further work, of increasingly specific relevance, can build. The work has contributed to understanding of the definition and relatedness of multiple species (their taxonomy) and relative risks from some *Xanthomonas* diseases. So, for example, the team is contributing genomic data on over 1000 *Xanthomonas* strains into publicly available databases, including the re-classification of some pathovars and the identification of new pathovars and species of *Xanthomonas*. This means that future work by themselves or others can use this resource to develop plant disease diagnostics with precision. Future assays will make it possible to detect and identify various *Xanthomonas* pathogens from plants or seeds, in laboratories, borders or even in the field.

Similarly, cutting-edge genetic techniques were used in screening for resistance to some *Xanthomonas* species. For example, resistance to important races of Xcc was found in specific *Brassica* lines, with some lines having combinations of resistance; the identification of markers for these resistances will contribute to accelerating breeding efforts. Novel tools to non-destructively visualise Xcc in brassica tissues were used to study disease progression and transmission. This revealed movement of Xcc from infected leaves to seeds, as well as demonstrating seed transmission to the next generation. These findings can underpin future work in breeding for resilience in such crops and contribute to disease control.

Impact steps

The project team members have been building credibility as a trusted partner. They have held conversations with Defra and several seed companies, breeders and growers associations regarding findings. The team took the initiative to be helpful, as a pro-active step toward engaging with the Risk Register: they have systematically compiled information on bacterial pathogens, and they have also identified gaps in genotypes for bacterial pathogens by checking the Risk Register, along with sequencing data generated in this project, publicly available genome sequences and the National Collection of Plant Pathogenic Bacteria. Providing this useful information should further build trust. They have recommended adding bacterial leaf streak of maize (caused by *X. vasicola pv. vasculorum*) to the Plant Health Risk Register and regulating it as an imminent threat accordingly. More generally, Defra team members have been keen to discuss the diagnostics element of the work, particularly in relation to horizon scanning and national security. Project team members have also visited two large seed companies to gradually develop important underlying Conceptual Impacts – 1) an appreciation of the power and utility of genomic/molecular research in making discoveries relevant to understanding and dealing with *Xanthomonas*-caused plant diseases, for instance by informing diagnostics and 2) an appreciation of work towards molecular marker development to assist screening for resistance to *Xanthomonas* species. Demonstrating an Enduring Connectivity impact, through the team's interacting in a positive, often informal way over several years e.g. characterising bacterial isolates, testing plants and being willing to give presentations, a very large *Brassica* seed company has accelerated its contacts with the team, clearly impressed by its expertise, and seems poised to become a partner.