Final Project Summary

AHDB CEREALS & OILSEEDS

Project title	Multiple herbicide resistance in grass weeds: from genes to agroecosystems.		
Project number	RD-2012-3807	**Final Project Report**	PR601
Start date	01/05/2014	**End date**	31/08/18
AHDB Cereals & Oilseeds funding	£310k	**Total cost**	£3.1 million

What was the challenge/demand for the work?

The project addresses the challenge of herbicide resistance in black-grass, a major constraint on the continued sustainable production of winter wheat in the UK. This problem has continued to grow in scale despite a long history of applied research, much of it carried out in a series of programmes of limited scale. This project seeks to address the scale of the challenge with a major integrated programme spanning from basic to translational research in scope and from the molecular to agroecosystem in scale.

How did the project address this?

The project has addressed five key questions: what is the molecular physiological basis of multiple herbicide resistance (MHR)? What is the extent and impact of MHR? What are the major drivers of resistance evolution? Can applied evolutionary models aid in resistance management? What are the economic and environmental consequences of novel weed and resistance management? Each question has been addressed in integrative work packages delivered by partners at the Universities of Newcastle and Sheffield, Rothamsted Research and the Institute of Zoology. Each work package has been linked to outputs that have been made available to the UK farming sector in the course of the delivery of the grant, accelerating the transfer of research knowledge to the community.

What outputs has the project delivered?

The programme has delivered all the projected outputs associated with the individual work-packages (WPs). Importantly, it has also delivered some high level outputs in forming a community of researchers who have delivered the Black-Grass Herbicide Resistance Initiative (BGRI). The BGRI have raised the profile of weed science both nationally and internationally, an output that can only assist the UK's reputation as a centre for agricultural innovation in the future. The BGRI have delivered an impressive set of academic and outreach activities (see annex) and specific outputs of more applied value include.

1) **The development of a commercial diagnostic BReD**, a pocket device to detect non-target site resistance (NTSR) in black-grass. A world first in herbicide resistance testing, BReD represents a 12 minute simple semi-quantitative test for NTSR in black-grass (and other grass weeds) and is based on the detection of the protein AmGSTF1, discovered to be a NTSR functional biomarker of NTSR in grasses. The status of AmGSTF1 as intrinsically linked to NTSR in diverse populations of black-grass collected across the UK has been validated as part of the resistance audit (see 3). BReD will continue to be developed and commercially available to the arable industry following the end of the project through its commercialisation by partner company MoLogic (www.mologic-bred.co.uk/).

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2) The generation of intellectual property, through the filing of patent WO 2018/138498A1 by the Newcastle group in 2018 detailing the identification of a new generation of herbicide resistance biomarkers that can serve as the basis of both new diagnostics and targets for chemical inhibition by herbicide synergists.

3) A national audit of resistant blackgrass populations linked to previous management practice. Repeated annual field-surveys have resulted in the creation of a database documenting black-grass density for ~200 UK fields over 2014-2018, with associated field management data back to 2004. The resistance status of 132 of these surveyed fields was measured through assaying for herbicide resistance, identifying the current widespread extent of resistance to the herbicides 'Atlantis' (mesosulfuron), 'cheetah' (fenoxaprop), and 'laser' (cycloxydim). Statistical analysis linking the management histories with resistance status from WP2.1 has confirmed that there is a strong positive relationship between the historic intensity of herbicide use, and both current black-grass population density, and herbicide resistance. This has been published in the journal Nature Ecology and Evolution (DOI: https://doi.org/10.1038/s41559-018-0470-1).
We have additionally measured the density of blackgrass in over 5000 locations from 2015-2017 allowing us to build up a national scale picture of the distribution of the weed. This work has allowed us to correlate the density of blackgrass with rainfall, land use and soil type. This then allows us to identify areas at risk of future spread of blackgrass. This work has been submitted to the journal Ecology Letters for publication.

4) The research resource of a characterized collection of herbicide resistant blackgrass populations. The BGRI project has generated a unique collection of ca. 200 black-grass populations with extensive data on the phenotypic, genotypic and mechanistic basis of herbicide resistance. These characterised populations have been pivotal to outcomes reported in 3) and 5). Access to these populations has facilitated a CASE PhD studentship with Bayer to explore the diversity of MHR mechanisms, as well as studies to explore population genetics of black-grass, informing the extent of gene flow (dispersal) within- and between-populations. In addition, a unique set of 400 pedigreed blackgrass seed families were created and screened for herbicide resistance and plant life-history / fitness characteristics. Results have been used to quantify the additive genetic-variance underpinning variation in sensitivity to herbicides (including glyphosate), and to calculate the heritability and genetic correlations underpinning ecological traits including flowering times and reproductive fitness. This is a unique black-grass genetic resource, and is facilitating further experiments into the genetic architecture of NTSR at Rothamsted Research.

5) Underpinning knowledge that can help reduce the likelihood of resistance evolution
Statistical approaches have been developed to combine data on molecular mechanisms of resistance, herbicide tolerance status and the history of weed management status. Analyses show that whereas target site resistance (TSR) mutations are significantly associated with intensive use of individual herbicide MOAs, application of herbicide mixes containing multiple MOAs are significantly associated with markers of NTSR. Taken together (with results in 3), these results clearly establish that herbicide diversity alone is not sufficient to mitigate evolution of MHR in black-grass. Resistance screening has been further extended to the herbicide glyphosate (beyond the original project scope and objectives). Results highlight significant variation in glyphosate sensitivity amongst populations, with some populations showing survivors at field rate application doses (540 g ha^{-1}). Analysis has shown that

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current glyphosate sensitivity has a heritable genetic basis for selection to act upon, and is significantly correlated with the historic intensity of glyphosate use in these populations. These results suggest that black-grass populations are evolving resistance to glyphosate and add urgency to current calls for glyphosate stewardship to minimise risks of evolution of resistance.

6) Converting predictive models of herbicide resistance to on farm decisions
We developed predictive models of the evolution of TSR and NTSR, and black-grass density, in response to different control strategies (e.g. herbicide, cultivation, crop rotation). We used these models to find optimal integrated weed management strategies over a 10 year time horizon. This allowed us to convert our understanding of black-grass population ecology and evolutionary dynamics to practical, economically sustainable, management strategies in the face of evolving resistance. We show that cost effective management requires knowledge of how black-grass affects crop yields, an important piece of ongoing work we are addressing using our farm management and black-grass density database. We also show that as resistance evolves optimal weed management strategies should rely more on non-chemical, agronomic control to maximise long-term profitability.

7) Environmental and economic valuation of cost and mitigation of resistance. We developed a new model to allow us to estimate national-scale yield loss and economic cost due to herbicide-resistant black-grass. The annual winter wheat yield loss across England is 1 million tonnes and the annual cost to the farming community is £0.5bn. This is being submitted to the journal Nature Sustainability. We also developed a new modelling framework to allow concurrent estimation of productivity and economic outcomes as well as environmental end points. This modelling framework is being used in ongoing work assessing trade-offs and synergies using our farm management and black-grass density database and also for future blackgrass mitigation scenarios.

8**) Community of practice**. The BGRI has established stakeholder and farmer focus groups and met frequently with those groups to discuss project outcomes in a range of workshop type events. The establishment of a national blackgrass monitoring network has been integral to the success of the BGRI and has depended on close collaboration and participatory research with UK farmers. The BGRI team have attended and presented annually at the Cereals event and at a number of industry, farmer and agronomist events, including the Association of Independent Crop Consultants annual conference (2017 and 2018), and NFU workshop on resistance management and many others (see Annex). Internationally, members of the BGRI consortium were active contributors to the Global Herbicide Resistance Challenge meeting, presenting and helping to organise workshops, raising the profile of the UK as a centre of agricultural research.

9) Predictive tools: the data from the monitoring programme has allowed us to develop a series of models that predict the density of blackgrass as a function of management (e.g. rotation, herbicides, cultivation). Using these models we can better evaluate the effectiveness of alternative management strategies. We have found, for example, that techniques such as spring cropping can be spatially and temporally extremely variable in terms of their effectiveness. This work has been published in Pest Management Science (https://onlinelibrary.wiley.com/doi/abs/10.1002/ps.4759).

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Who will benefit from this project and why?
The beneficiaries of the project are. 1. **UK Arable Farmers**- the programme has sponsored the development of new technology and management knowledge that is bespoke to the national context of herbicide resistance and gives growers unique insight and tools in preventing and mitigating against the problem going forward. 2. **The National Crop Protection Research Community**- through the delivery of this large and integrated research programme, the BGRI have raised the profile of UK research in Weed Science and more broadly agronomy related research at an International level. 3. **The Agritechnology Industry**- the programme has developed a world first pocket diagnostic that has elicited international interest in its deployment in other grass weeds and raised the awareness of innovation in agritechnology in the UK. 4. **The Academic Community-** has acquired new knowledge of molecular mechanisms and the evolution of resistance to chemical control agents that add vital knowledge to our understanding of acquired resistance to other agrochemicals, drugs and antibiotics. 5. **Research Training in Agronomy**- the project has trained a total of nine young postdoctoral scientists in the latest molecular and modelling approaches that can be applied in crop protection, providing new highly skilled scientists to the sector. **6. Industry** the modelling tools and data resources generated in this project are being used in follow up projects with SMEs and large industry partners (e.g. 2Excel Aviation, IBM, Syngenta). **7. Policymakers** – the economic and productivity costs estimated in this project are useful baseline data for any future resistance management policies.

If the challenge has not been specifically met, state why and how this could be overcome
The project has met or exceeded all of its original objectives. The key challenge that now needs to be addressed is the application of the knowledge, tools and technology developed in the programme into widely adopted new weed management strategies. These efforts are currently underway. Additional funding has been secured by Rothamsted Research to extend monitoring across the black-grass farm network to 2020, providing additional power to interpret how farmers are responding to the black-grass resistance epidemic and to develop evidence-based approaches to black-grass management. Seed populations from the network will be screened for resistance to pre-emergence herbicides and there will be ongoing monitoring of changes in glyphosate sensitivity. Rothamsted and Sheffield, together with industry partners IBM, 2Excel Aviation and Syngenta are seeking ISCF funding (application date; 24 October 2018) to extend these efforts towards the establishment of national monitoring and data platform for black-grass management and decision support.

Lead partner	Newcastle University
Scientific partners	Rothamsted Research, University of Sheffield, Institute of Zoology
Industry partners	The following industry partners have actively engaged in the course of the project; MoLogic (commercial partner), Frontier Agriculture, ADAS, Bayer Crop Science, 2Excel Aviation, IBM, Centre for Crop Health and Protection
Government sponsor	Biotechnology and Biological Sciences Research Council

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