Institution: University of Warwick

Unit of Assessment: A5 – Biological Sciences

Title of case study: Improving Farming Strategies by Modelling Herbicide Resistance in Weeds

1. Summary of the impact

Decreased crop yields caused by the evolution of herbicide-resistant weeds are a global threat to agriculture and food security. Evolution of weed resistance to the herbicide glyphosate is particularly prevalent in North and South America, where genetically modified glyphosate-resistant crops are widely grown. Research carried out at the University of Warwick between 2008 and 2013 and led by Dr Paul Neve, in collaboration with industry and academia, has resulted in the development of computer models to simulate the evolution of glyphosate resistance in weeds. This modelling research identified new, more sustainable farming strategies for the use of this technology, such as avoidance of sole reliance on glyphosate and more effective ways to manage the timing of herbicide application. These recommendations have been disseminated widely throughout North America by the attendance of Neve and project collaborators at grower conferences, workshops and road shows, and have also attracted associated press coverage. The research has fundamentally changed farmer and industry management of genetically modified herbicide-resistant crops by providing new plant growth guidelines that are being used to combat herbicide-resistant weeds; for example, providing the cotton growth guidelines used for 75% of this crop in the mid-southern USA.

2. Underpinning research

Research by the Neve group focuses on the genetic, ecological, evolutionary and agronomic factors that drive the evolution of herbicide resistance. Neve has worked in this area for 14 years and is a recognised international expert. In 2007, the company Syngenta wanted to fund research developing modelling frameworks to address the economically significant problem of evolution of resistance to glyphosate in North America. Academic collaborators from several US universities, including the University of Arkansas and Iowa State University, were identified. Key underpinning research has included the identification and characterisation of some the world's first glyphosate-resistant weed populations, and studies on the genetic control of resistance and the fitness effects of resistance alleles in the presence and absence of selection. This research has provided fundamental insights into the genetics and evolutionary ecology of glyphosate resistance.

Computer-based simulation models that incorporate current knowledge about herbicide resistance can be used for both research and management of farming strategies. By modelling the development of weed resistance, researchers can investigate the effects of different management strategies on the emergence and prevalence of herbicide-resistant weeds. The new models developed by the Warwick team and their collaborators at the Universities of Kansas and Iowa State have built on previous approaches to develop complex demo-genetic models (based on population genetics) that incorporate parameters to describe aspects of various species' life histories, the genetic determination of herbicide resistance and management factors. In doing so, the models have been able to examine how selection pressure for resistance is moderated by the timing of herbicide application in relation to the age distribution of the population, leading to the identification of more effective strategies for the timing of weed management interventions.

Mixture and rotation of modes of action of pesticides has been a central tenet in resistance management, though often without substantive 'proof of concept'. Modelling work by Neve and collaborators has explored the basic requirements for these strategies to work in reducing the evolution of herbicide resistance. Selection pressure (in this case from glyphosate) is clearly a major determinant of the probability and rate of evolution of resistance. Reducing the use of this herbicide and retreating from a system that relies totally on glyphosate-tolerant crop technology are key requirements for sustainable management, but models have also clearly demonstrated that management strategies that reduce glyphosate use at the expense of overall levels of population control are counter-productive. Despite the apparent reductions in selection pressure, the risk of glyphosate resistance is elevated where weed population control is not maintained, mainly because the mutation supply rate (the frequency of beneficial mutations) for resistance is increased. Hence, underpinning empirical research by Neve has provided insight into the genetics

and evolution of glyphosate resistance. Ongoing research, funded by Syngenta (see section 3, Grant funding), has involved a postdoctoral researcher within the Neve group. Current modelling research by the group is designed to expand the context and application of these models by incorporating quantitative genetic traits, fitness costs associated with resistance and spatial aspects of the evolution of resistance. This modelling effort is being complemented by a four-year BBSRC CASE studentship that is exploring the molecular mechanisms, inheritance and fitness consequences of novel resistance traits. This research has identified previously unreported costs associated with resistance mechanisms conferred by massive levels of gene amplification.

Warwick Staff

Dr Paul Neve, Assistant Professor, School of Life Sciences (**2004 to present**) has acted as the primary investigator on all grants relating to this work, first conducting the modelling research and then supervising postdoctoral researcher Melissa Bridges. **Mr Andrew Mead**, Teaching Fellow, School of Life Sciences (**1987 to present**) has provided statistical and modelling input to projects. **Dr Melissa Bridges**, Post Doctoral Research Assistant, School of Life Sciences (**2012 to present**) worked on a Syngenta-funded glyphosate resistance-modelling project.

Collaborators

Professor Jason Norsworthy, University of Arkansas, USA provided expertise in biological and weed management inputs to the model and disseminated modelling results to the agricultural industry in southern USA. **Professor Ken Smith**, University of Arkansas, USA provided expertise in chemical weed management in southern USA. **Professor Mike Owen**, Iowa State University, USA provided expertise in weed biological and weed management inputs to the model as well as dissemination of modelling results to the agricultural industry in mid-western USA. **Mr Chuck Foresman**, **Dr Ian Zelaya**, **Dr Deepak Kaundun** and **Dr Les Glasgow**, Syngenta Crop Protection, provided expert input on chemical weed management in genetically modified herbicide-tolerant cropping systems in the USA.

3. References to the research

Peer-reviewed publications:

1. Neve P. *et al.* Modelling glyphosate resistance management strategies for Palmer amaranth (*Amaranthus palmeri*) in cotton. *Weed Technology* (2011) Vol. 25, 335–343 (http://dx.doi.org/10.1614/WT-D-10-00171.1).
2. Neve P. *et al.* 2011. Modelling evolution and management of glyphosate resistance in *Amaranthus palmeri*. *Weed Research* (2011) Vol. 51, 99–112 (http://dx.doi.org/10.1111/j.1365-3180.2010.00838.x).
3. Neve P. Simulation modelling to understand the evolution and management of glyphosate resistance in weeds. *Pest Management Science* (2008) Vol. 64, 392–401 (http://dx.doi.org/10.1002/ps.1495).

Grant funding:

1. Experimental evolution of resistance to herbicides in *Chlamydomonas reinhardtii*. Leverhulme Trust, 2009–2013, Amount awarded £183,962
http://www2.warwick.ac.uk/fac/sci/lifesci/research/weedecologyandmanagement/chlamydomonas/
2. Modelling evolution of glyphosate resistance in US cropping systems, Syngenta Crop Protection, 2012–2014, £228,000
http://www2.warwick.ac.uk/fac/sci/lifesci/research/weedecologyandmanagement/glyphosate/
3. Novel informed modelling approaches to investigate the evolution and management of herbicide resistance in *Alopecurus myosuroides*, BBSRC Industrial CASE studentship with Bayer Crop Science, 2011–2015, (Grant Ref BB/I01652X/1) Amount awarded by BBSRC £91,932, amound awarded by Bayer Crop Science £10,000
http://www.bbsrc.ac.uk/pa/grants/AwardDetails.aspx?FundingReference=BB%2fI01652X%2f1

4. Details of the impact

Weeds present a major global challenge to food security, accounting for more crop yield loss than both pests and diseases in many areas. Glyphosate is the world's most important herbicide and

genetically modified glyphosate-tolerant (Roundup Ready™) crops are grown on over 100 million hectares of land. A large increase in glyphosate use occurred when Monsanto introduced Roundup Ready crops in the mid-1990s, resulting in the widespread and often exclusive use of glyphosate for weed control. These changing use patterns were accompanied by the widespread evolution of glyphosate resistance in weeds, which is now estimated to impact up to 60 million hectares of agricultural land. Neve's underpinning research, modelling efforts and supporting data from subsequent fieldwork, have increased our understanding of how herbicide resistance, and in particular glyphosate resistance, evolve over time. Agritech companies have traditionally used field trials to research the development of herbicide resistance, but the limited success and lack of practicality of this has led to large global companies such as Monsanto using Neve's more efficient modelling approach (evidenced by letter of support[a]). The ability to assess hundreds of different management scenarios using these modelling frameworks has ultimately resulted in recommendations for the proactive management of glyphosate resistance. In particular, this research has demonstrated that integrated weed management and the use of herbicides with diverse modes of action can reduce the development of glyphosate resistance. The disadvantages of over-reliance on genetically modified glyphosate resistant crops and the need to adopt proactive measures to mitigate the evolution of herbicide resistance have been made clear. Modelling research has translated this knowledge and understanding into practical 'on the ground' management guidelines for farmers using genetically-modified crops, including the adoption of more soil-residual herbicides and the rotation of several modes of action (evidenced by letter of support[b].

The results of this research have been widely and effectively disseminated by Neve through interactions with US academics and the agrichemical industry. In February 2008, Neve presented results to the National Soybean Breeders Association in St. Louis, USA and to the International Weed Science Congress in Vancouver, Canada. These conferences, with over 500 delegates each, are attended by industry representatives and academics. Many US academics have a role in outreach and hence presentation to these audiences provides a very effective means of ensuring that results are communicated to growers and their advisers. During visits to the USA, Neve has frequently been interviewed by specialist press outlets as well as taking part in field days and webinars arranged for the press (evidenced by press coverage[c-f]). The involvement of Professors Norsworthy and Smith from the University of Arkansas has provided a way to communicate these results widely to farmers in the areas worst affected by glyphosate-resistant weeds. Outreach events, including workshops, field days and meetings, have enabled important messages on the management of herbicide use to be conveyed to thousands of producers, growers and consultants. The impact of this extensive outreach work is substantial, with the current herbicide recommendation for cotton, which is a "*direct result*" of Neve's modelling work, being used on approximately 75% of cotton in the mid-southern USA (evidenced by letter of support[f]).

The results generated have been used internally and externally by Syngenta to inform decisions related to marketing and product stewardship. The research was nominated for a Syngenta research award. Syngenta and Monsanto scientists and regulatory staff use modelling outputs to demonstrate the value of resistance management to their marketing departments. These recommendations have been formulated into product stewardship recommendations that are widely disseminated at meetings and conferences to growers, consultants and academics. Key personnel within Syngenta and Monsanto are members of the Global Herbicide Resistance Action Committee and results are also communicated through this platform (evidenced by letter of support[a]).

The evolution of resistance to herbicides is recognised as one of the major threats to global food production, resulting in severe economic hardship to farmers, loss of crop yield and a reduction in land values. In extreme circumstances, where populations of weeds such as Palmer amaranth get out of control, farmers must resort to hand weeding at an additional cost of $50 to $100 per acre. More than 10 million acres of Roundup Ready glyphosate-resistant cotton are planted in the USA each year. Over 150 million acres of corn and soybean are produced and results are currently being extended to these cropping systems. Economic costs of evolved glyphosate resistance are severe (evidenced by letter of support[h]). The herbicide models developed by Neve have provided new crop management regimes to prevent evolution of resistance as well as providing evidence recommending the benefit of more diverse, less environmentally harmful integrated weed management.

As a result of development of these models and their application, Neve is now recognised as a global expert on herbicide resistance management. He is a member of the UK Weed Resistance Action Group and Chair of the European Weed Research Society's working group on herbicide resistance, both of which bring together famers, industry and government bodies to coordinate management recommendations. Neve is regularly invited to speak at a range of events, including industry meetings and multi-disciplinary forums, such as the Global Herbicide Resistance Challenge International Conference (Perth, February 2013).

5. Sources to corroborate the impact

a. **Letter of Support; Global Herbicide Resistance Lead**, Monsanto (Identifier 1)
b. **Letter of Support: Product Biology Herbicide Lead for Latin America**, Syngenta Crop Protection, Colombia (Identifier 2)
c. **Press Article:** Expert on resistant weeds researching Arkansas case. *Delta Farm Press* (Aug 3, 2007) http://deltafarmpress.com/expert-resistant-weeds-researching-arkansas-case
d. **Press Article:** Computer modeling shows importance of early-season weed control in tackling resistance challenges. *Delta Farm Press* (28 Dec 2012) http://deltafarmpress.com/modeling-shows-importance-early-season-control-tackling-weed-resistance
e. **Press Article:** Looking for ways to beat the weeds. *The New York Times* (16 Jul 2013) http://www.nytimes.com/2013/07/16/science/earth/looking-for-ways-to-beat-the-weeds.html?pagewanted=all&_r=0
f. **Press Article:** Weed worries won't wane. *Crop Life* (1 Mar 2012) http://www.croplife.com/article/24935/weed-worries-won-t-wane
g. **Letter of Support: Professor and Elms Farming Chair of Weed Science**, University of Arkansas (Identifier 3)
h. **Letter of Support: Global R&D Crop Protection Lead-Corn**, Syngenta Crop Protection, Inc. (identifier 4)