A Nuffield Farming Scholarships Trust Report

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AHDB Cereals & Oilseeds
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Blackgrass:
System BEN offers alternative solutions to resistance management

Ben Taylor-Davies

May 2017

NUFFIELD UK

NUFFIELD FARMING SCHOLARSHIPS TRUST (UK)

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A Nuffield (UK) Farming Scholarships Trust Report

Date of report: May 2017

"Leading positive change in agriculture. Inspiring passion and potential in people."

Title	**Blackgrass:** System BEN offers alternative solutions to resistance management
Scholar	Ben Taylor-Davies
Sponsor	AHDB Cereals & Oilseeds and Three Counties Agricultural Society
Objectives of Study Tour	To discover if there was anything in the rest of the world that could be applied in the UK in order to provide better control of blackgrass where herbicides are failing.
Countries Visited	Canada, USA, Argentina, Chile, Peru. Uruguay, Paraguay, South Africa, Poland, Belarus, Russia, Mongolia, China, Australia
Messages	• Chasing science often leads to ignoring the basics. • Become more technical in the understanding of soil texture. • Increase understanding of blackgrass biology. • Herbicides are not the answer. • Don't confuse the issue with cover crops. • GMO seed is not suitable for the UK. • Glyphosate is under terrific pressure. • Cultivations are vital. • The BEN system will provide a sound basis for winning the war against blackgrass.

EXECUTIVE SUMMARY

Blackgrass has become the greatest problem in British arable farming. Whatever method is used to control it the blackgrass remains one step ahead. Blackgrass is gaining resistance to almost all herbicides in the United Kingdom, and herbicides it is not already resistant to are likely to succumb soon. Blackgrass thrives better in heavier and wetter soils than most UK combinable crops, so it is able to produce a large amount of seed which is shed before harvest. It is highly competitive within arable crops and reduces yields by as much as 80% where heavy infestations occur. In many ways, blackgrass can be described as the 'perfect weed'.

The classification of soils as 'heavy' or 'light' needs changing immediately. The classification of 'medium' has been omitted on purpose as most growers like to describe themselves as either 'heavy' soil farms or 'light'. Countries other than the UK quantity soil texture percentage and this gives a far clearer image of what the soil actually is. Aerenchyma is the reason blackgrass is able to survive in wetter soils. A simple definition of that term is: air pockets in the roots that allow diffusion of oxygen from the stem to the root tip.

"Martian" is the name given to a plant which is an invader from another continent or country (e.g. Japanese knotweed) which, if all its ecological requirements are favourably met, will reproduce so strongly as to become a serious issue. Darwin's Origin of Species theory and the process of natural selection are crucial when trying to understand blackgrass (in fact any weed, or indeed any living organism). The simplest example is herbicide resistance, where plant mutations resistant to the herbicide are able to reproduce and the progeny will continue to be resistant to the herbicide. "Mutations" can relate to drilling dates, soil disturbance, cropping and anything to do with blackgrass.

Little herbicide research has been conducted in 20 years because of the release of Roundup-Ready seeds in countries that permit GMO crops to be grown. The international research industry slashed budgets by 90% overnight and didn't predict glyphosate resistance would occur. GMO seed for total herbicide resistance must be avoided in the UK! More glyphosate applications in-crop in a conservation agriculture scenario will place the UK firmly in the fast lane for glyphosate resistance.

Cover crops and soil health are extremely fashionable topics, which generally means someone is making a profit! There are as many pitfalls to growing cover crops as there are advantages. Cultivations are absolutely crucial for blackgrass control, as they are the only thing that can effectively control blackgrass apart from herbicide. They are especially important in stale seedbed scenarios where they remove any glyphosate-surviving plants.

The BEN system of farming is the first system developed that uses an understanding of the blackgrass plant and works with nature - rather than constantly fighting against it - to effectively manage the blackgrass problem.

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CHAPTER 1: Introduction

I was born on the family farm in Ross-on-Wye, Herefordshire on the south east border of Wales with England during the long hot summer of 1976, and was delivered on the night our hay and straw barn burnt down! The farm had soils ranging from red sandstone to deep fertile alluvial silt, which allowed a good range of cropping. Historically it was a mixed farm enterprise but eventually turned all arable in the late 1980s, as so many farms in the area did at the time.

I attended the University of Liverpool and it was during my finals that the typical farming-father-and-son discussion took place about succession. It culminated in a pile of Farmers Weekly publications being left on my desk, with a note which read: "Go get a job". A BSc Hons in Geography, specialising in oceanography and palaeontology, hadn't really been a career-driven choice of topics: the main attraction had been the fact I would have only 6 hours of lectures a week for 3 years and, assuming I passed at the end of the 3 years, my parents would be thrilled!

Reality finally struck as I began poring through the adverts with my girlfriend, Helen (now my wife). The only job that looked a possibility was as a trainee agronomist with the Wisbech-based firm Hutchinsons, who had a depot at Ledbury, Herefordshire. It looked like an ideal opportunity to live at home whilst working 'away'. In view of the number of applicants who had applied I was fortunate to be offered a trainee appointment and was allocated a position in Banbury, Oxfordshire.

Figure 1: The author, Ben Taylor-Davies

From day one I loved the job of agronomist and it coincided with the real issues of blackgrass herbicide resistance in Oxfordshire during the late 1990s. This is where my passion for learning about this weed began to develop. Whatever we did, blackgrass was always one step ahead; in many ways you could describe it as the perfect weed! Fortunately during the next decade or so, new active ingredients were brought to market by chemical manufacturers and they kept up with the development of the highly adaptable blackgrass plant until Atlantis was released. Atlantis came with the stark warning: "This is the end of the line for the foreseeable future."

The year was 2003 and I had just married Helen, the girlfriend who had helped me scan the Farmers Weekly's looking for a job!

By 2011 Atlantis was becoming less effective with resistance building fast. Three children had come along - daughters Tegan and Erin and son Jobe - and we were now living back on the farm. The daily *commute into Oxfordshire to work as an agronomist continued. Life was good.*

But 28th September, 2012, was the day that changed everything. That evening Helen was sat by Jobe's bedside in intensive care in Birmingham Children's Hospital. A kick to the side of his head by a horse had smashed his skull and all that was contained within it. Jobe was given a less-than-5% chance of living after receiving one of the most serious head injuries the hospital had ever had to deal with. Seconds seemed like weeks during the time he was in a coma but after 16 days of highs and lows, Helen was able to hold her son again for the first time. Jobe stayed in hospital for many more months and then eventually came home to a father who became terribly protective of his family and struggled to leave them for any length of time. He was suffering from post traumatic stress syndrome.

By the spring of 2015 I was still suffering from the syndrome and it was at this time Helen sat me down and said: "*We are fine, Jobe will be the boy he'll be, we don't need protecting any more, you need to get back your passion, your enthusiasm and your love of being challenged. Before Jobe's injury you had mentioned undertaking a Nuffield Farming Scholarship. Now is the time to follow that up, and we as a family will be with you on every step of your journey."*

I class myself fortunate to have been selected as a 2016 Nuffield Farming Scholar and cannot thank the Nuffield Farming Scholarships Trust and my sponsors highly enough for giving me the opportunity: not only to learn about my subject, but far more importantly to give me back my independence, my drive and my passion.

I remember explaining to my clients that I was determined to visit the four corners of the earth to find solutions. In the end I travelled for 21 weeks covering 128,000 miles. Four corners? Yes, and also half way to the moon!

My Nuffield Farming Scholarship has taken me on many different journeys including the physical, the mental, the metaphysical, the delusional, and back. Helen, Tegan, Erin and Jobe, my family, I thank you for your unwavering support.

Chapter 2: Background to my study subject

Growing up on a family farm in Herefordshire, I was blessed with being involved in growing many crops, which included potatoes, sugar beet and Brussels sprouts, on good fertile soil. Blackgrass was unheard of (thankfully still is to this day) and couch grass was beginning to become controlled by the expensive but highly effective herbicide 'Roundup'. The wild oats were hand rogued in June and the only other grass weed was annual meadow grass, a grass weed that remained green through harvest and would attract the falling dew, thus preventing late night combining.

1992 was the last year that stubble burning was permitted. It was just something you did to get rid of excess straw and allow a clean field for ploughing. I was the scuffle operator, who would prevent the fire from spreading to hedges, buildings and straw stacks! There had been a few mishaps here and there in previous years, but the last year before the ban, all went well.

1995 was the greatest year for profitability in our farm's history: our wheat yields reached 10 tonnes per hectare sold, and the whole UK arable sector was thriving. Fertiliser prices were low, with ammonium nitrate costing £76 per tonne and red diesel 9p per L. I remember that spring with interest. Driving a Fiat 760 with dual wheels and a power harrow, I spent hours trying to work a small patch of 'heavy' ground in order to create a fine enough seedbed for sugar beet planting. It would be many years later when, as a trainee agronomist working for Hutchinsons and walking some exceptionally water-logged soil on the outskirts of Oxford, I realised that the word 'heavy' was totally relative. At home, 14% clay content was considered heavy, yet here in Oxfordshire the clay content was measured at 91%!

When I began work as an agronomist the standard treatment for blackgrass in wheat and barley was 5L of IPU (isoproturon), costing the grower about £16 per hectare, for broad leaved weed control. The addition of DFF (diflufenican) to this mix would tidy up most things for the winter. Avadex (Triallate) was used where wild oats were a big problem. By the time Isoproturon was banned in 2008 (due to its contamination of water courses) its effectiveness on blackgrass was almost zero due to herbicide resistance.

Despite the release of more and more herbicides, blackgrass remained a problem in cropping in the UK. As blackgrass became resistant to one chemical this would more than coincide with the release of another to take its place. Crop rotation has always been practised on most UK farms. However, driven by profits as the price volatility of the 2000s struck, many farms that were unable to grow high value crops were pushed into a winter-wheat/winter-oilseed-rape rotation, or continuous wheat. This rotation relied heavily on the new herbicides being brought to market, and when the stark warning came with the release of Atlantis (mesosulfuron-methyl + iodosulfuron-methyl-sodium) in 2003 that there were no new herbicides in the pipeline, things needed to change!

However, although the anticipated resistance by blackgrass became reality, changes on farm only happened slowly. As an agronomist during this time, rather than become defeated by the prospect of losing the fight against blackgrass, I saw it as an opportunity to explore the weed. How could it be controlled in the absence of effective in-crop herbicides; living with the real prospect of many herbicides becoming banned; and little in the way of development of new chemical active ingredients?

Blackgrass must be one of the most highly researched weeds in the UK. However the messages from researchers, scientists, farmers, social media, machinery manufacturers, agronomists and agrochemical manufactures seem to be some of the most controversial and opposing of any set of opinions within agriculture.

My Nuffield Farming study therefore looked to critically appraise methods of blackgrass control and what is of value to the UK. Using studies and information I have gathered from around the globe, I aim to provide a better understanding of the consequences that result from the blackgrass decision-making process and at the end suggest a strategy which might overcome the problem.

Chapter 3: My study tour

As my study tour offered an opportunity to explore the globe looking at arable farming systems, all with their own particular issues when it came to weed control, I decided to take every chance to learn that presented itself.

USA - June/July 2016.

When I flew into Minot airport the security guard on the Canadian border asked what I was doing in North Dakota? Explaining I was on holiday, he replied: “Nobody takes a vacation in North Dakota, what are your really here for?” “Herbicide resistance and weed control” I replied, and with that he just looked up with one eye and said “So you are one of those dumping pesticides into the Mississippi delta and the reason half the Gulf of Mexico is poisoned; have a nice day!”

It was then I realised I needed to be prepared to talk informatively about my subject because I could and would be challenged anywhere about this potentially political hot potato. My travels took me through 20 states which included the Canadian border with North Dakota, South Dakota, Iowa, Kansas, Colorado, Illinois, Tennessee, Mississippi, and eventually finished on the Texan coast. As I drove the 8000 miles of this zig-zagging route around the USA I visited many universities, growers, innovators, herbicide manufacturers and research institutes, all of which had their own opinions, problems and solutions to the ever-growing problems of weed management.

South Africa - August 2016.

South Africa is historically a country with fantastic resources used in agriculture throughout the African continent where very differing weed control challenges are posed. Investment into agricultural research has somewhat dwindled, but I was fortunate enough to meet many retired government research scientists along with those who, despite the lack of funding, are producing some excellent and very useable data. I travelled from Cape Town to the Sandveld, extensively through the Western Cape, Kwazulu-Natal and the Free State. All have their very particular climate, soils and weed challenges.

Brazil - November 2016.

The red country! The enormity of the country is only matched by the enormity of the first farm I visited in Mato Grasso, at 400,000Ha. Groupo Bom Futuro must be regarded as one of the world’s largest arable farms. Their openness and generosity with their time to show me all things ‘weeds’ was fantastic. I travelled in the states of Goias and then Parana, the latter of great interest as family farming was still the norm and where topography and farm size were similar to that of the UK. It was here I also saw some of the latest work on adjuvants (products that aid the efficacy of an agrochemical) as an aid to help the performance of herbicides.

Argentina - December 2016.

I was hosted throughout my whole stay in Argentina by the weed scientist, Martin Vila-Aiub, who was from the university of Buenos Aires. We mainly visited the provinces of Buenos Aires and Cordoba and met with some interesting growers, scientists and herbicide manufacturers. The farms might have been smaller on average than in Brazil but, even so, one was 110,000 Ha and had some excellent in-house farm trials that took a day to walk around.

Peru - December 2016.

I was invited to the city of Cusco in the Peruvian Andes, situated at 11,000 feet, the air pressure so low that if one was in an aeroplane, oxygen masks would be deployed. Yet the Incas (early 13th century – mid 16th century) grew great crops and even had a research centre - Moray. Here the temperature could be manipulated by as much as 15°C and a tour of their ancient and modern research facilities was indeed a highlight.

UK + Europe - Various 2016/2017.

Rather than list individual places and in an attempt to keep things concise, I will simply say I was fortunate enough to travel to France, Belgium, Germany and Poland by train as I made my way further through Belarus, Russia, Mongolia and eventually China. The journey encompassed Russian Siberia with its ultra-short growing season (it was frozen at the time of my travel) as well as the arid climate - and very distinct possibility of total desertification - in the Gobi desert in Mongolia. The trip was awe-inspiring.

China - February 2017.

I was unsure if I had been taken sufficiently out of my comfort zone and decided to plan a 3-week tour of China. What an amazing experience in every way, but only made possible by the wonderful translator I had accompany me during the duration of my stay. I travelled from Beijing's Hebei Province by bullet train through Shandong, Jiangsu, Zhejiang, Jiangxi and eventually ended up in Hong Kong. Knowledge transfer was at the forefront of all discussions I had, and I left with a very positive and progressive image of Chinese agriculture and how they overcome their weed issues.

Australia - March 2017.

This was the final destination for my Nuffield Farming study tour and, quite honestly, I had left the best experience until last. I have previously travelled extensively through Australia and know the country well. Australian weed issues are possibly the most challenging anywhere in the world and they have had a huge head start on the UK with their resistance issues. The excellentAustralian support network in terms of funding has proven their research as second to none. An extremely busy 3 weeks saw me spending a week in Western Australia, a week in South Australia and a week split between Queensland and New South Wales.

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It seemed every time I left a country I had a new idea about the ways to progress knowledge in the UK. Whilst a few places contradicted each other, the challenge would be to organise the knowledge gained in such a way that it could be applied to the UK. This approach would have to make scientific sense rather than be based on myths, legends or a quixotic ideal.

Chapter 4: Blackgrass fundamentals

Blackgrass (*Alopecurus myosuroides*) has its origins in the Mediterranean region and is considered to be naturalised in the UK as it has been found here since records began. Blackgrass decimates yields in UK arable crops, especially combinable crops. In a country that was pushing yields of winter wheat to 12 tonnes a hectare across a range of farming types in 2006, blackgrass became an increasing problem. A typical yield map (shown below) of a client's Tewkesbury farm shows how heavy infestations (800 heads per square meter) of blackgrass can reduce yields of winter wheat from 11 Tonnes a hectare (shown on the map in dark green) to 3 Tonnes a hectare (shown in dark red). The colours of light green, yellow and orange show a reduction in yield simply as a dynamic of how much blackgrass is present.

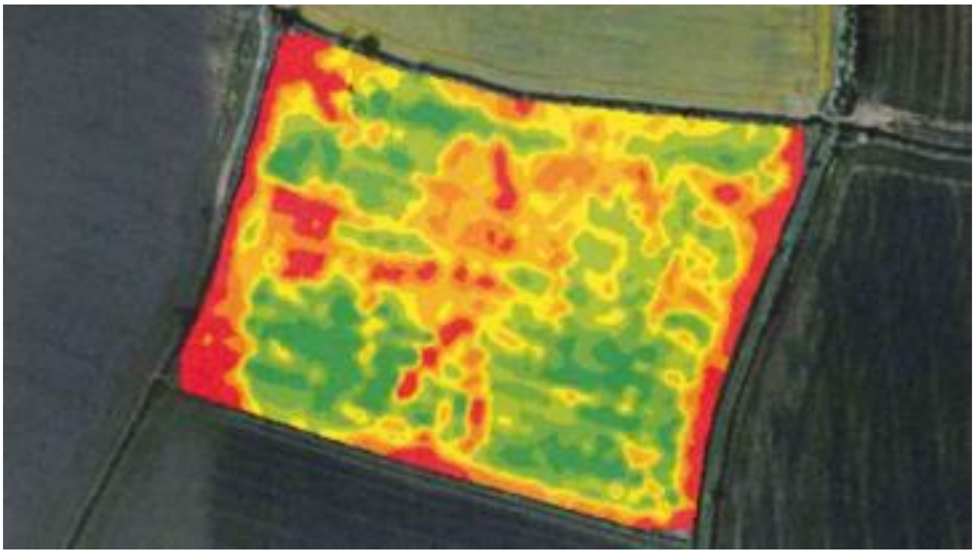

Figure 2: Yield map showing blackgrass infestations

4.1. Blackgrass competition

Whilst many would consider blackgrass a highly competitive plant, evidence would suggest differently. Whilst growing and competing within an arable crop, the plant is highly aggressive. Yet, beyond a natural arable crop, the plant is seldom found in any other part of the UK environment. Surely a competitive plant would be found in unsprayed fence lines, grassland, scrub areas or in hedgerows? Dick Neale (Hutchinsons UK) has shown at the Brampton Blackgrass Centre of Excellence that, whilst blackgrass is an early coloniser of freshly cultivated ground, if left for a number of years, then other plants soon outcompete it. By Year 5 of the trial, blackgrass had been totally outcompeted. This was with an incredibly high density of seedbed blackgrass.

Blackgrass has been described as the 'perfect weed' by many in the industry and it is hard to argue against this. It generally emerges after a crop has been planted; is resistant to herbicides; highly competitive; can thrive in wet soils; produces huge seed numbers and sheds its seed before harvest. This is accepted the UK over, and therefore concentration on blackgrass control is based on interrupting its ‘perfect’ environment. I have studied blackgrass extensively throughout the UK and northern Europe as well as during my world travels and have seen it grown in many scientific laboratories to be used as a model for other grass-weed studies.

Figure 3: Ryegrass near Buenos Aires, dominant in fence lines - highly competitive

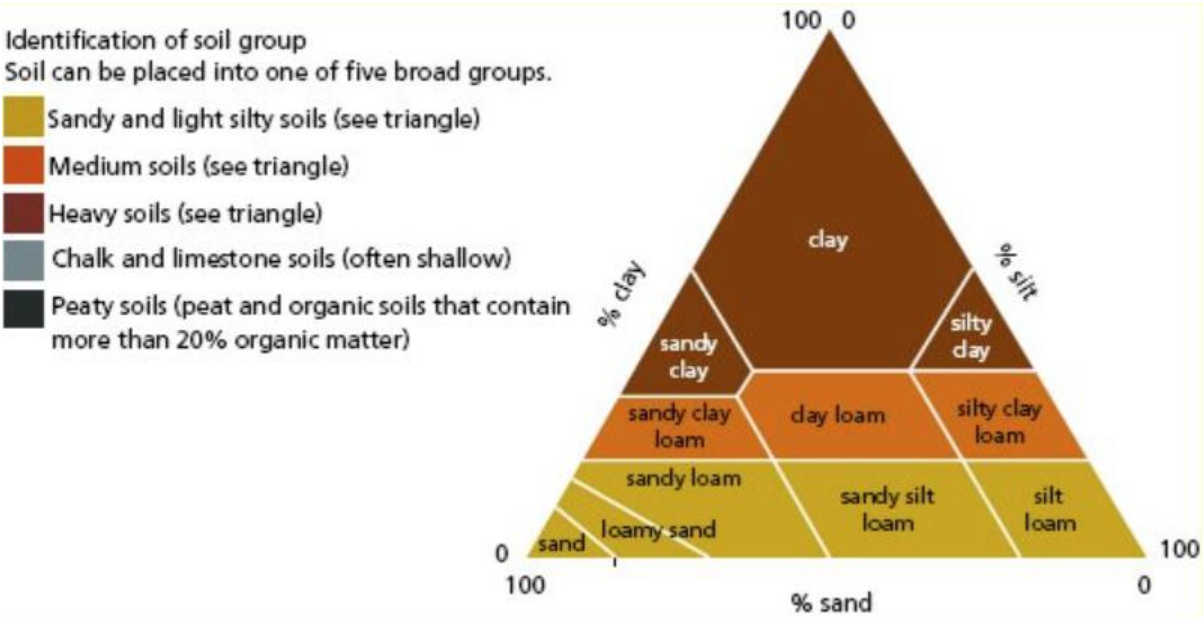

Figure 4: The soil triangle and interpretation of 3 main soil types
(*Soil Protection review, 2010 cross compliance handbook*)

4.2. No such thing as a 'heavy' soil

"Blackgrass thrives in heavy, poorly drained soils". This would be the viewpoint of most, if not everyone, when they think about blackgrass. The problem of identifying what a 'heavy' soil is causes much confusion and frustration. During my travels throughout the world, the initial questions from growers were: what tractors do you have? what crops do you grow? and … what is the clay percentage of your soil? These were three basic questions asked time and time again, from Londrina in Brazil to Shandong in China. The answers to the first two questions are easy to give. However in the UK how many growers/agronomists actually know the true percentage of clay/silt/sand content of the soils they are working with? Many use Figure 4 on the previous page to give an overview of what soil conditions they are working with i.e. 'heavy', 'strong' or 'light' … none of which give an indication of what soils are actually like.

The Soil Protection Review, first launched in 2010, grouped soils into three categories: heavy, medium and light. Heavy soils were potentially grouped into just one category whether they had 30% clay and 70% sand, or 100% clay! Five of my UK clients were asked to provide a sample of what they considered was 'heavy' soil and the variance in the results was shocking! The samples contained 27% clay through to 92% clay! What was classed as 'heavy' by one farmer was considered as 'maybe light' for another. This sort of generalisation must change - and change fast.

Figure 5: Soil samples: all classed as 'heavy' by each individual farmer: what is heavy to one may be considered 'light' by another.

4.3. Know your enemy

Having a basic understanding of what blackgrass actually looks like in the seedling and early development stage of the plant's life is absolutely critical in areas which blackgrass has not yet infected, and where growers are trying to prevent its spread onto their farms. Blackgrass typifies farming in general in that those that need to have the greatest eye for scouting their fields for the very first appearance of the weed often don't know exactly what they are looking for; whereas those whose fields are already infected know exactly what it looks like! It would be wrong to go into identification details in this report as this knowledge is readily available through agronomists and the internet. One excellent booklet is by Bayer Crop Science UK cropscience.bayer.co.uk/mediafile/.../m27534_bg_expert_guide_2015_210x148.pdf. However, what is important is the understanding that if you haven't got it, it is well worth taking the time to learn about blackgrass and what it looks like in order to try and keep blackgrass under control when it does infect. **Blackgrass is not so much a question of if, but when.**

Figure 6: Blackgrass emerging in winter barley

Blackgrass, or slender foxtail, has been in the UK for many years, but it was seldom written about or identified as a huge problem until the late 1970s. The problem has then become progressively worse up until the current day. An article written in 1894 by *Wright et al.,* mentioned that "*slender foxtail was the product of bad farming*" and goes on to explain how the weed becomes a problem where bad rotations, hoeing, planting conditions, crop competition and soil management can lead to "*infestations of slender foxtail*".

Figure 7: Blackgrass resistance to selective herbicides in Banbury Oxfordshire.
Front plant obviously dying, back plant thriving

Herbicide resistance has been an ever-growing problem. From the mid 1980s - 2000s the pace of herbicide development kept up with the pace of blackgrass itself forming resistance. Products, such as IPU, began to be banned because of their environmental profile, and the last product launched in 2003 - Atlantis - came with the caveat *'this is the end of the road for new chemistry (for this weed) for the foreseeable future,'* and so it proved with resistance soon becoming an issue. Identification is quite simple in a population. See the photo on previous page, taken in Banbury, Oxfordshire. This shows plants resistant to selective herbicides in the background and appearing perfectly healthy, while others in the foreground are dying.

4.5. Stubble burning

Much has been written about the ban on stubble burning and how this has led to the huge rise in blackgrass populations and herbicide resistance issues. However, even when stubble burning was still permissible, it was well recognised that blackgrass was becoming an increasing concern and resistance issues to herbicides were also becoming a problem (*Stephen Moss*). Interestingly during the parliamentary debate discussing the proposed stubble burning ban in 1989, not one MP mentioned the resulting problems associated with weed control. Exploring the reintroduction of stubble burning would prove futile due to the environmental considerations, not only through air pollution, but also the environmental impact on soils.

4.6. Current control advice

Table 1 (figure 8 on next page) is generally accepted as listing the best controls for blackgrass where herbicide resistance is a major issue - and it seems wherever there is blackgrass in the UK there is also resistance (*Stephen Moss*).

The adoption of spring cropping is spreading fast throughout the UK as is delayed drilling of winter wheat, plus using higher seed rates to provide crop competition. Farmers generally prefer not to plough because seedbed creation following ploughing can mean destruction of soil structure while minimum tillage or no-till drilling can enhance it. Fallowing would be a useful option: however, this is uneconomical on the majority of farms. See Table (figure 8) on next page.

4.7. Allelopathy

Allelopathy, the process by which plants are able to communicate with each other through root exudates, has been identified but as yet is mainly unproven in the UK, with further work being required and associated papers written. The only work currently available in the UK looks at the allelopathy between blackgrass plants themselves that therefore controls which and how many will grow. Blackgrass produces root exudates as it begins to grow and signals to other blackgrass seeds. If the likelihood of competition with its own species is deemed too high then the seed will wait for another opportunity to germinate. This is why not all blackgrass germinates at once and therefore requires a stale seedbed to control it.

Multiple stale seedbeds i.e. the process by which the blackgrass or other weeds are led to believe they are competing in a crop without the crop being planted, are therefore required to have the greatest impact on the blackgrass population and assist the decline in the seed bank as much as possible prior to planting of the commercial crop.

Method	% control achieved Mean	Range	Comments
Ploughing	69%	-82% to 96%	Rotational use has potential benefits
Delayed autumn drilling (by ~3 weeks)	31%	-71% to 97%	The later the better – but increased risk
Higher seed rates	26%	+7% to 63%	The higher the better – but lodging issues
Competitive cultivars	22%	+8% to 45%	Useful, but marginal effects
Spring cropping	88%	+78% to 96%	Effective, but challenging on heavy soils and limited herbicide options
Fallowing/grass leys	70-80%/year (of seed bank)	–	Absence of new seeding critical

Based on a review by Lutman, Moss, Cook & Welham (2013).

Figure 8: Table based on a review by Lutman, Moss, Cook & Welham 2013

Figure 9: Dr Leslie Weston (University of Wagga Wagga) with the latest delivery of machinery used to measure the allelopathy of plants.

Allelopathy can be seen the world over. For instance ryegrass in South Africa was planted between the rows of vines in vineyards to protect the soil from erosion, but the vines produced 34% less fruit where the ryegrass was growing. Also in South Africa in the Western Cape, the variety of spring wheat SA88 was shown to have twice the allelopathic effect on ryegrass as on any other variety *(Dr Pietersen University of Stellenbosch).*

Dr Leslie Weston and her team at the Charles Stuart University Wagga Wagga, Australia, firmly believe in allelopathy. Although that contention is hard to prove, the university has just invested $55 million AUD of which the major proportion will be spent on looking at the allelopathy of one plant by another and to try and quantify and measure the results.

The most interesting work in the UK concerns the huge seed return of blackgrass visible in a field of winter wheat in Oxfordshire that was then planted into a ryegrass ley for silage. Despite many viewings of the ryegrass and, at times, a fingertip search, the absence of any blackgrass plants was astonishing. This could only have been due to allelopathetic effect as the seed bank contained a huge quantity of viable blackgrass seeds.

Chapter 4 Summary

1. Blackgrass first became a major problem for arable farming in the late 1970s.
2. Blackgrass colonises freshly cultivated ground but is not competitive in undisturbed ground.
3. It is an annual weed and produces a huge amount of seed.
4. Can develop resistance to herbicides
5. Not all blackgrass seeds germinate at once and can communicate via allelopathy.
6. Multiple stale seedbeds would be needed to control all germination
7. Blackgrass could be described as ‘the perfect weed’.

Chapter 5: Aerenchyma - the root of the problem

It was during a lunch meeting at the University of Western Australia that Dr Colmer, who specialises in producing crops in waterlogged conditions, explained the concept of aerenchyma. His definition (see 5.3) was backed up during various meetings throughout China, and also with the rice growing expert Dr Xaing Wengju at the Beijing University of Agriculture. His explanation covered:

5.1. Ethylene

It is commonly known that many plants growing in waterlogged conditions and therefore anaerobic conditions (air pockets in the soil being filled with water) suffer stress, and roots are known to produce excess ethylene. Ethylene at low levels is an important hormone for the formation of flowers and fruits of the plant but, as concentrations increase, ethylene plays a large role in plant senescence (the process of deterioration with age) and therefore plants begin to show yellowing of leaves and, if waterlogging continues, the plants eventually die.

5.2. UK crops growing in wet conditions

It is widely apparent that various plants in UK arable systems react differently to waterlogging. Oilseed rape for instance almost immediately shows signs of stress, and senescence of the plant follows on quickly afterwards. Cereals seem to have a better resilience to waterlogging, but senescence still occurs after a relatively short time. Blackgrass seems to survive waterlogging better than either winter oilseed rape or cereals. Grass meadows also survive waterlogging well and that is why in areas where there is high rainfall and a lot of waterlogging, grass is usually grown instead of arable crops. Wales, the Lake District and Scotland are all examples of this.

Figure 10: Oilseed rape grown on variable soil type, following a relatively wet winter. The waterlogging is all too apparent with the rape unable to survive, allowing blackgrass the freedom to grow without competition.

Figure 11: Oilseed rape and blackgrass in waterlogged patch in a field in Banbury, Oxfordshire showing blackgrass survival but rape unable to survive

The common acceptance that blackgrass loves wet and waterlogged conditions, neither helps explain or understand how and why it thrives. An investigation into why it copes so well in those soil conditions might help to provide a solution to its control.

5.3. Root oxygen requirement

Dr Colmer, an expert in cropping in waterlogged conditions, explained how aerenchyma worked and how it allowed plants to 'breathe' during waterlogged conditions. Firstly he explained that a plant's roots require oxygen in order to maintain health. Usually the oxygen is supplied through the soil, and of course, when waterlogged, water fills the air spaces in the soil and creates hypoxic conditions in the plant's roots. This leads to the root producing excess ethylene and the rapid onset of senescence and plant death. Rice however is very different compared to cereals and brassica crops. It is commonly known that rice grows very well in hypoxic conditions in flooded paddy fields, which I observed during my travels throughout China. Dr Colmer explained this was due to the formation of aerenchyma within the roots.

5.4. Aerenchyma's role

Aerenchymae are variable in their appearance and development; however it can be assumed in simplest terms that they are an open pathway which allows oxygen movement from above the soil or water level, down to the roots. The roots are then able by diffusion to pass the oxygen down to the root tip before it diffuses into the soil keeping the roots - and therefore the plant - healthy. In a normal scenario, oxygen however would also diffuse into the soil as it passed down through the aerenchyma. Aerenchyma are either present at all times, or form in the cortex by elongating and joining cells of the cortex when the plant is subjected to hypoxic conditions. The formation of aerenchymae during this phase is very reactive to the roots' requirement for oxygen.

5.5. Suberin

Suberin is an apoplastic barrier at the outer cell layers of the roots that reduces radial oxygen loss (ROL) from the aerenchyma and prevents toxic compounds from entering the root (*Source: Watanabe et al., 2013*). It aids the diffusion of oxygen through the aerenchyma to the root tips, although the composition and full role is not yet understood. Hansjoerg Kraehmer (ex Bayer in Germany) kindly provided confirmation that indeed blackgrass has the ability to produce aerenchyma and suberin and supplied the photographs below taken under a micron microscope.

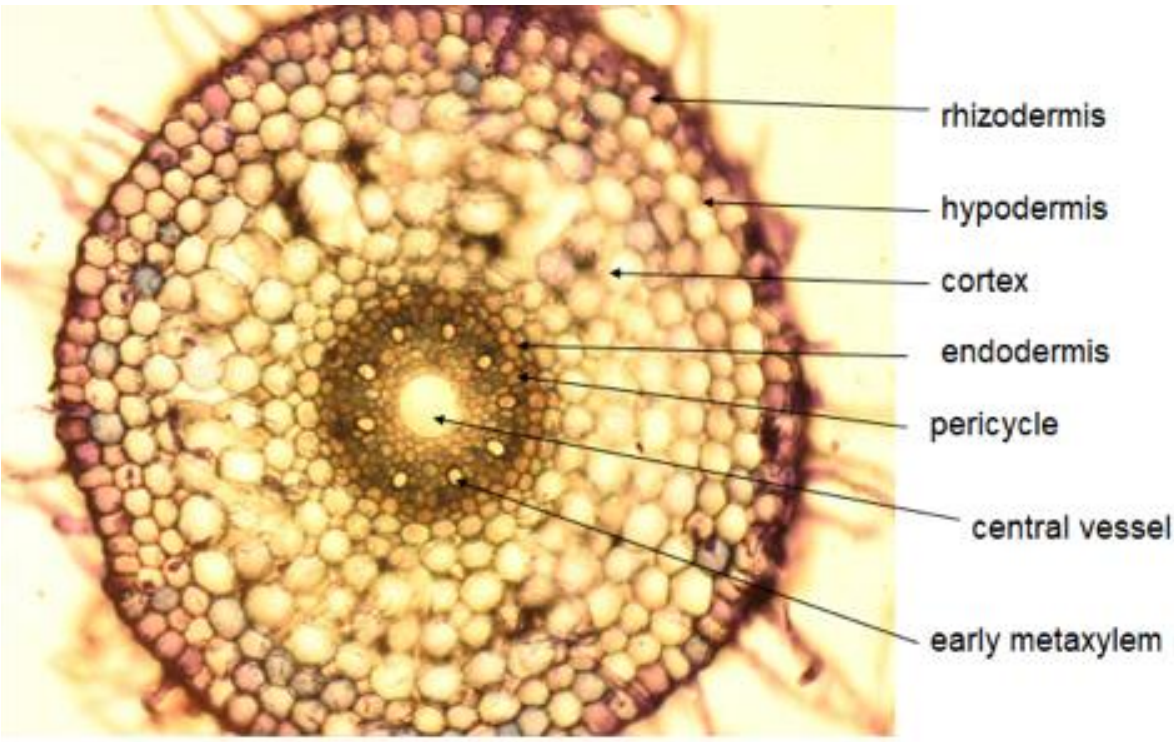

Figure 12: Transverse section of blackgrass root showing location of cortex
The photos in Figures 12, 13 and 14 were kindly supplied by Hansjoerg Kraehmer (Bayer, Germany)

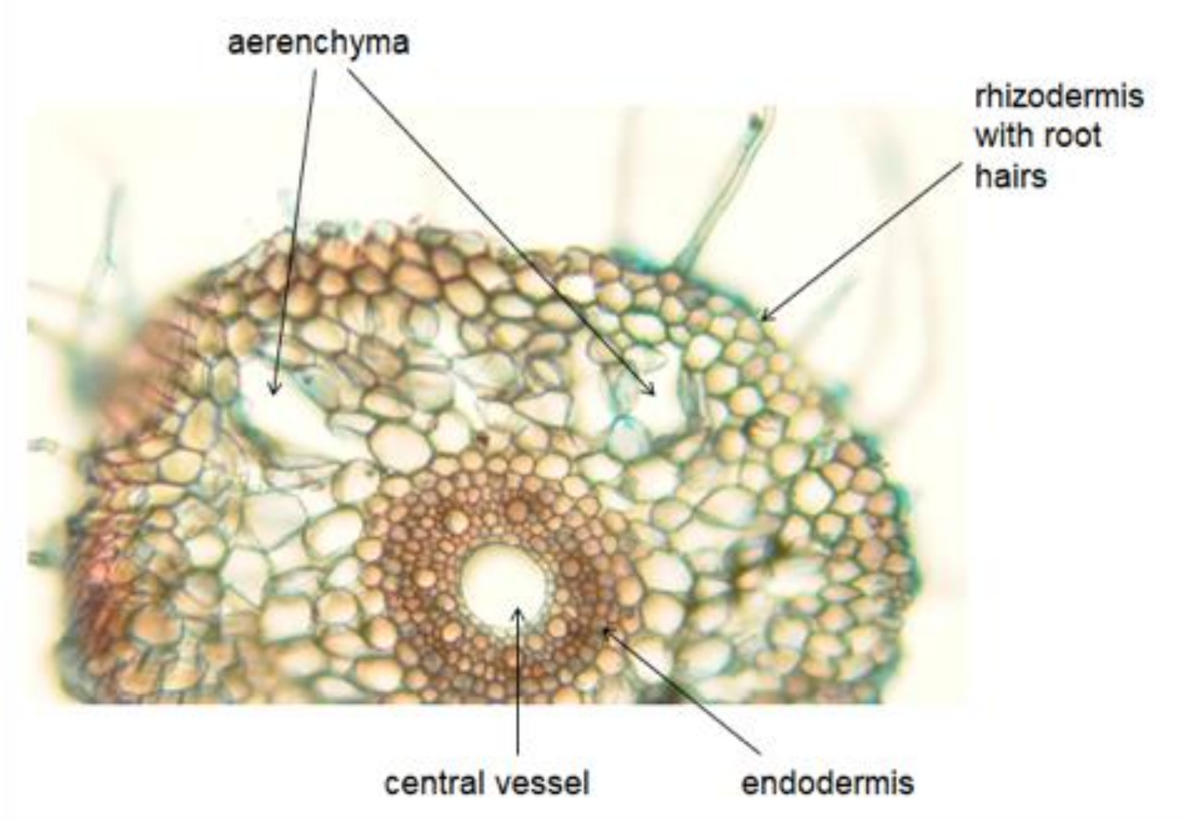

Figure 13: Transverse section of blackgrass root showing aerenchyma formation

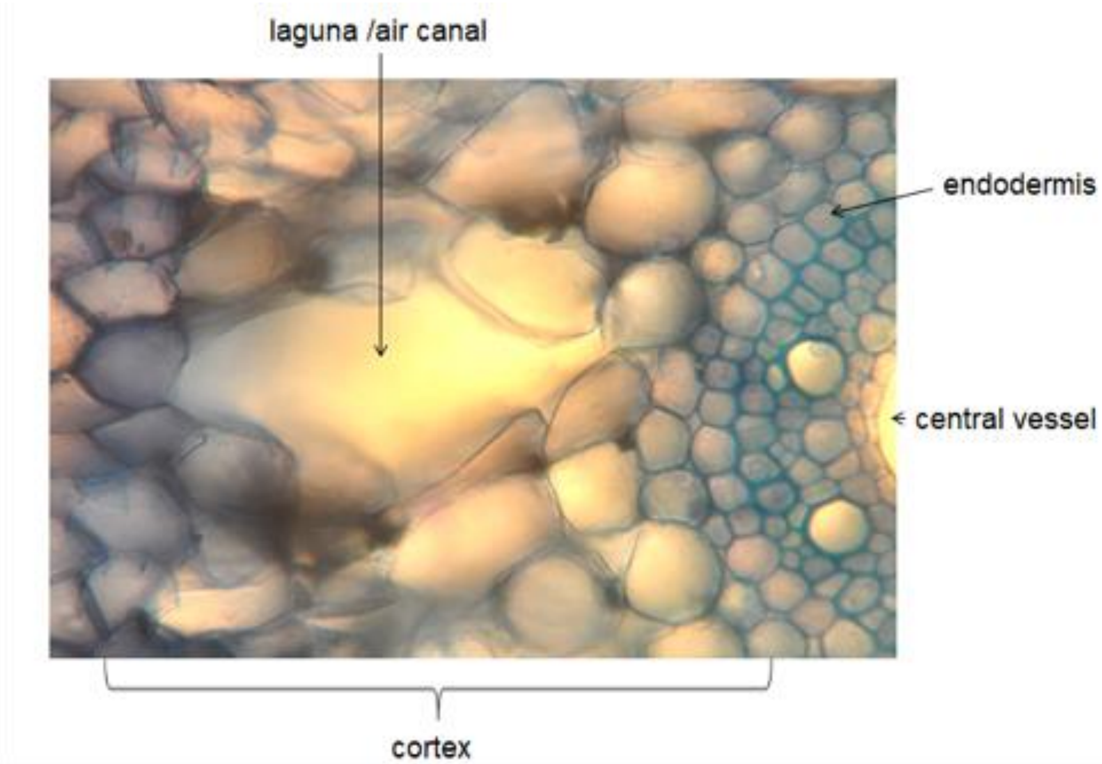

Figure 14: Transverse section of blackgrass root showing aerenchyma and the passage of oxygen (stained with toluidin blue) magnification 400x (Hansjoerg Kraehmer)

Knowing that blackgrass has the ability to produce aerenchymae in hypoxic conditions and therefore survive waterlogging for longer, it is interesting to note that brassica species (including oilseed rape) have no ability to produce aerenchymae. Cereals, although they have a small ability to produce it, are not able to withstand hypoxic conditions for very long.

5.6. Wheat for waterlogging?

Wheat has a very small amount of ability to produce aerenchymae. However a wild relative can produce it very well, and during laboratory experiments in the University of Western Australia, Dr Colmer tried crossing modern day varieties with the wild relative. Whilst the new strain actually grew and produced aerenchymae, the seed viability that was produced was lower than 3%. Funding for further research trials to take place was withdrawn.

Chapter 5 Summary

1. Waterlogged conditions can cause plants to die but blackgrass seems to have a higher resilience than most arable crops.
2. Aerenchymae allow oxygen movement from above soil level to plant roots
3. Blackgrass is able to withstand wet conditions longer than cereals can.
4. Brassicas including oilseed rape have no aerenchyma and therefore cannot withstand any water logging

Chapter 6: Darwin - back to basics

158 years ago, Charles Darwin published "On the **Origin of Species** by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life" and it is considered to be the foundation of evolutionary biology. However it took many years for this paper to become accepted as the scientific explanation for how species have developed their individual traits.

6.1. From the Galapagos finches to the author's dogs

Darwin studied the finches of the Galapagos islands and realised that although each finch was related to a common South American ancestor, individual finches had been naturally selected to suit the environment for which they then found themselves, and this was as much to do with bill morphology than anything else. Natural selection occurs because of mutations within a population. Some mutations will benefit the adaptions of the species, other mutations will hinder it, those that thrive ultimately become the norm.

Darwin realised that the bill of each finch on each island had adapted to the food source on that island, with some of the finches' bills being very strong in order to crack nuts, whilst others had grasping bills in which to catch insects. Some of the finches had developed the ability to feed on cactus, whilst others on fruit. All of them were dependent on the island in which they were found. Darwin concluded that natural selection by the finches that had adapted to their environment would cause them to thrive and produce similar offspring. Those offspring with the best adapted bills would thrive on the food source and therefore natural selection by the finches developed a diverse bill depending on where and what was required of it.

Figure 15: Collection of the author (Ben Taylor-Davies's) dogs - all the same species but selected for totally different traits.

Darwin's theory can be attributed to not only finches of the Galapagos, but to every element of flora and fauna found on earth that has been manipulated by man in order to artificially select for desirable traits which he would benefit from. This applies from dog breeding and the diversity of breeds (Figure 15) - although all still *Canis lupus familiaris* - to the selection of wheat varieties; and the artificial selection of higher yielding wheats or wheats with desirable traits for disease avoidance; for straw length; or for its bread making ability. Darwin concluded that the *speed of evolution = genetic diversity x population size*. In the UK calculations have been made to assume the annual seed production of blackgrass to be 1 trillion seeds. The genetic diversity and mutations that can be found in this population are almost unimaginable when comparing the genetic diversity and mutations found in Earth's population of 7 billion humans.

6.2. Dr Mike Ashworth and Yuna wild radish

The theory and practice are obvious and readily accepted. The effect of selection on weeds is also incredibly important when understanding blackgrass and looking at ways to solve the problems. On my visit to the University of Western Australia, I spoke with Dr Mike Ashworth who has written a fabulous paper where he looks at one of the greatest weed problems found in the west of Australia - the wild radish. The paper looks at how artificial selection can change the natural population of the wild radish and how fast these results can be produced.

	Selected for early flowering (5 generations)	Control Yuna wild radish (WARR7)	Selected for late flowering (3 generations)
Days to first flower	29	59	114
Growing degree days to first flower	344	634	1414

Figure 16: Table by Ashworth, M Walsh, M Flower, K Vila-Aiub, M & Powles, S 2016
Directional selection for flowering time leads to adaptive evolution in Raphanus raphanistrum (wild radish)

The table above shows the control wild radish as having a flowering date at 59 days. The trial population then selected the first that flowered and the last that flowered and grew those seeds on. This was repeated over 5 generations in total. The results show that in just 5 generations of selection a wild radish was able to produce a flower as early as 29 days in the earliest selection trial and then as late as 114 days in the late selection trial. This shows how quickly plants are able to adapt depending on the environment that is selecting them.

6.3. Blackgrass selection

Knowing how quickly selection can change an annual weed population, thoughts obviously return to blackgrass. In a population of blackgrass sprayed with herbicide, a mutation of a plant that becomes resistant to the herbicide continues to grow, whilst those that don't have resistance are eradicated. The plant mutation that becomes resistant produces seeds that are also resistant and are shed to grow in the following crop. If they continued to be sprayed with the same herbicide they will multiply very rapidly within a few years. The mutation that causes herbicide resistance is a dominant gene and therefore remains in the plant's genetics when cross breeding. This explains why the re-introduction of old chemistry that hasn't been used for many years due to resistance remains ineffective many generations on.

6.4. A numbers game

Selection therefore is about the initial population and the higher that population the more mutations can occur. These mutations become successful if they are suited to their environment and reproduce large amounts of offspring. One blackgrass plant producing 200 seeds per head and with up to 60 heads per plant would mean a single mutation could produce 12,000 seeds in the first year. In the second year, all things being equal, this number could rise rapidly to 144,000,000. This of course assumes every seed is viable and the 60 heads per plant is reached. But it illustrates how prolific one mutation of a blackgrass plant can be within 2 years.

Figure 17: Impact of using weed surfer to remove seed heads

Figure 18: Impact of using weed surfer on individual plant

6.5. How fast?

Figures 17 and 18 show how a weed surfer removes seed heads from growing crops by chopping them off. "*In the first year the machine worked well as the blackgrass was well above the crop, but in each year following, the blackgrass seemed to shrink until in year 3 I couldn't use the machine*". Paul Dobson, Bellhurst Organic farm.

Chapter 6 Summary

1. Darwin observed that individual groups within a species adapted to cope with the conditions they faced
2. Annual seed production of blackgrass in UK equals an estimated one trillion
3. Herbicide resistant blackgrass mutations are dominant genes
4. If all nature followed Darwin's theory, then blackgrass would be no exception to selection and change.
5. Evolution is a numbers game, the greater the population the greater the diversity.

Chapter 7: Question everything - why?

A 6-hour drive from Buenos Aires led to me writing this chapter after discussing UK herbicide programmes with Dr. Martin Vila-Aiub. For many years the UK has used pre-emergence herbicides for two reasons. Firstly, they are the most effective chemistry at controlling blackgrass and this is true for many scenarios the world over for whatever weeds are being controlled. Secondly whatever the pre-emergence herbicide doesn't kill, will be sufficiently affected to be 'sensitised' to a follow-up post-emergence herbicide.

7.1. The sensitisation myth

Put simply, the pre-emergence herbicide half kills the weed, and the follow-up post-emergence herbicide finishes it off ….. "*Can't happen*," was the reply from Martin, *"in fact probably that method would lead to faster resistance occurring*."

As different modes of actions work at different sites in the plant, the impact on one part of the plant will not have an effect on a very different part of the plant. In fact: "*If you apply a post-emergence herbicide to a stressed plant, the chances are the herbicide will not be readily absorbed, thereby subjecting the plant to a sub-lethal dose of chemistry and a greater chance of the plant developing resistance quickly*." Dr Pieterssen (University of Stellenbosch, South Africa) confirmed that by subjecting sensitive ryegrass to sub-lethal doses of glyphosate, then a glyphosate-resistant ryegrass could be produced within four generations.

During the whole period whilst herbicides were working well, crops were planted between the end of August and middle of October. Very few spring crops were planted because they were less profitable and, in many instances, the rotation consisted of a 2-year wheat/oilseed rape rotation. It is therefore no surprise that blackgrass self-selected to germinate in the early autumn. For over three decades, constant selection pressure led to a blackgrass population that emerged from late August (when oilseed rape was planted) to mid October. As herbicides began to fail, blackgrass self-selected for early autumn became dominant in the rotation.

7.2 The peaks of the graph

So, as shown in Figure 19 on next page, delayed drilling of autumn cereal crops would allow all the selected blackgrass (see paragraph above) to have germinated first. The use of a non-selective herbicide, such as glyphosate, pre-planting, would result in a lower population of blackgrass to compete with the crop.

Spring cropping was also identified as an excellent effective way of controlling blackgrass. Very few spring crops used to be grown unless in a very wet autumn or when a winter crop had failed for whatever reason. Historically blackgrass would have been shaded out by strong winter crops planted in the early autumn, preventing blackgrass from germinating and competing in the spring.

Figure 19 shows exactly why drilling delayed beyond the steep germination peaks would provide low blackgrass pressure for the growing crop.

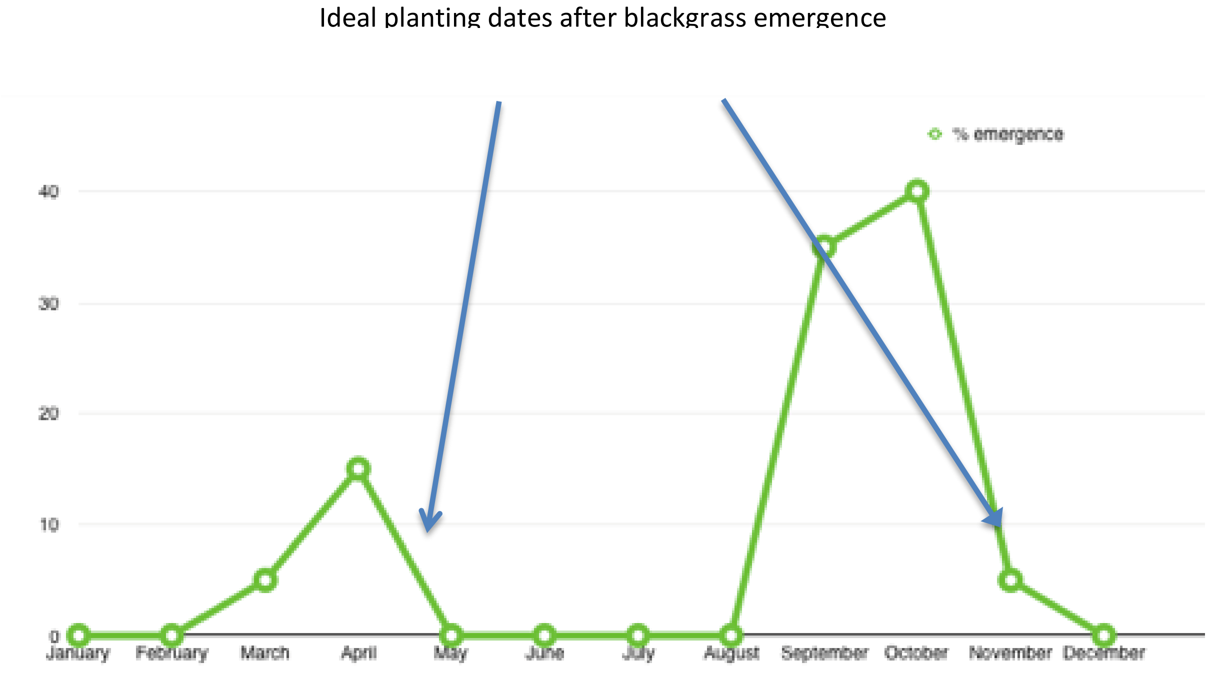

Figure 19: Clattercote Priory Farm, Banbury Oxfordshire. Blackgrass emergence pre 2003

However, this does not reflect the natural biology of blackgrass, but more so what the blackgrass has been selected for. As selection pressures change (i.e delayed drilling) so too will the population of blackgrass. Worryingly, as crops continue to be: drilled early (winter oilseed rape); drilling delayed until October/November (winter cereals); and spring cropping; the peaks of the germination graph will level out as the germination of blackgrass is spread over the whole 10 month planting season.

7.3. Clattercote Priory Farm

This is exactly what happened at Clattercote Priory Farm in Banbury, Oxfordshire. Figure 21 shows where, on the farm, spring crops and delayed drilling were introduced when the last effective herbicide was launched, knowing that there were no other herbicides in the pipeline for the foreseeable future. For 13 years the crop rotation (Figure 20 on next page) has led to a levelling off of the peaks and blackgrass has now self-selected to germinate 10 months of a year. The early excellent results of delayed drilling and spring cropping have become less and less effective for blackgrass control.

Despite following current advice, blackgrass levels and emergence patterns are getting more and more problematic to control. Selection pressure has and is being shifted and whilst it is claimed that there is a lower percentage of blackgrass emerging during the year, this is all dependent on the number in the first instance; and if the blackgrass is not being controlled in the crop the population can only increase. Ten per cent of 100 seeds per square meter will give 10 plants per square meter. This can rapidly rise to 1000 seeds per square meter and 10% would give 100 plants per square meter. In the arable crop, blackgrass levels at this density are extremely competitive and yield-robbing.

Year	Crop	Drilling month
1998	Winter Wheat	Mid September
1999	Winter Wheat	Early October
2000	Winter Rape	Late August
2001	Winter Wheat	Mid September
2002	Winter Wheat	Early October
2003	Winter Rape	Late August
2004	Winter Wheat	Mid September
2005	Spring Linseed	Mid April
2006	Winter Wheat	Late October
2007	Winter Rape	Late August
2008	Winter Wheat	Late October
2009	Spring Linseed	Mid April
2010	Winter Wheat	Late October
2011	Winter Rape	Late August
2012	Winter Wheat	Late October
2013	Spring Linseed	Mid April
2014	Winter Wheat	Late November
2015	Winter Rape	Early September
2016	Winter Wheat	Late November
2017	Spring Barley	Late March
2018	Spring????	

Figure 20: Table to show crop rotation on Clattercote Priory Farm

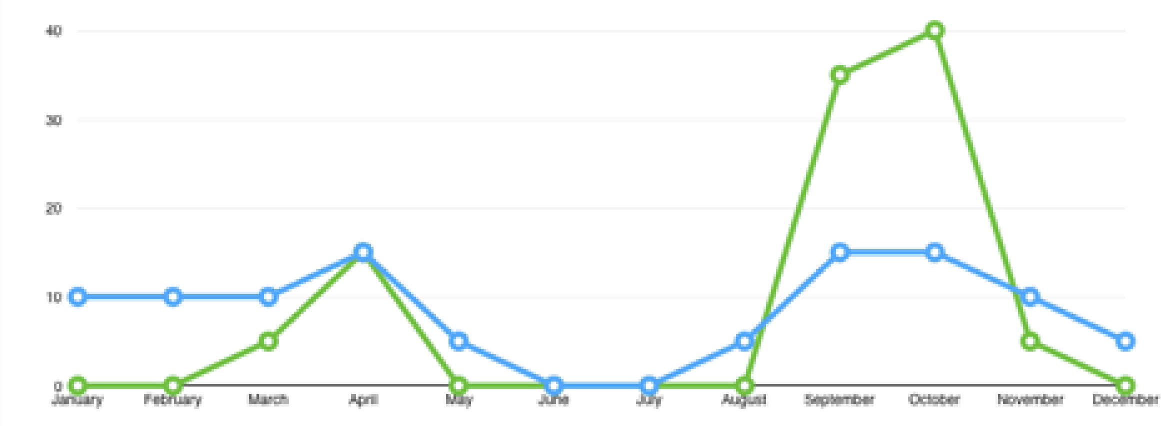

Figure 21: Clattercote Priory Farm blackgrass emergence patterns

The green line shows blackgrass germination percentage in 2003
The blue line shows blackgrass germination percentage in 2016

Chapter 7 Summary

1. Common practice in UK arable cropping is to use a pre-emergence spray followed by a post-emergence spray. But this creates resistance.
2. Delaying drilling or spring cropping can ultimately result in blackgrass self-selecting to germinate for up to 10 months of the year.

Chapter 8: Ecological niche - the Martians have landed

When travelling with weed scientist Martin Vila-Aiub of Buenos Aries University (Figure 22) throughout Argentina for a week, discussions were held about all aspects of weeds, weed management, and the scientific papers written about the subject.

Figure 22: Martin Vila-Aiub (Buenos Aries University)

Although blackgrass is not a weed issue in Argentina, Martin had a wide range of knowledge gained through reading papers, travelling the world and, more importantly, using blackgrass in laboratory work in Argentina from which other weed concerns could be modelled. Martin is currently involved with genotyping Johnson grass and looking at how this grass weed has become an established problem in Argentina. Johnson grass is not a native plant to Argentina (it originated from the Mediterranean region) and is therefore described as a Martian species. (A Martian plant is one originating in another country or continent). Martin went on to explain how all the problematic species of weed in Argentina are Martian species. He is currently in a collaborated study where the scientists have hypothesised that their Johnson grass has been imported, probably as contaminated seed from the USA, and can be traced back using genotyping.

Martin also explained the term 'ecological niche', a fantastic explanation for an organism that is in a Martian environment. A Martian environment fulfils every aspect of the organism's life cycle and so allows it to become dominant in its new environment. Martian species generally do one of two things when introduced: 1) find the new environment too harsh in which to survive in which case the species doesn't become established or 2) thrives in the new environment and establishes well, often to the detriment of other established species. In many cases the Martian species outcompetes native organisms, causing them to decline in their own natural environment. The Martian organism, in its original environment, will generally have been kept in check whether through predation, fungi, bacterial infection or constrained by the climate. These limits are seldom present in the new Martian environment.

In the UK, such species considered to now be living in an ecological niche would be: signal crayfish and grey squirrel, to the detriment of our native white clawed crayfish and native red squirrel. Not only do they out-compete their naturally closest relatives and often transmit disease that they themselves have become immune to, but they also damage the environment in which they live when that environment has not adapted.

Figure 23: Japanese knotweed pushing through tarmac

This is an example of a Martian plant: in the UK, Japanese knotweed is a plant that has become a huge problem as it had found its ecological niche, often being spread by water courses. Japanese knotweed is extremely aggressive and outcompetes many plants. As a ruderal (first coloniser) plant in its native Japan, it thrives on fresh volcanic lava fields where its strong rhizomes break up the rock. This is why it is able to break through concrete in the UK (Figure 23) and can cause serious damage in urban developments. In its native Japan, invertebrates, fungi and bacteria constantly attack the plant and therefore keep it in check. However none of these are present in the UK, and as there are no other close relatives either, Japanese knotweed is not kept in check. This leads to the issue of blackgrass.

Blackgrass originates from the Mediterranean but it does not thrive during their long, dry, hot summers. The UK and northern Europe have a wetter climate. As alluded to in chapter 2, aerenchyma allows blackgrass to thrive in wet and waterlogged conditions typically found on high-percentage clay soils in the UK; in poorly structured soils; plus farmed areas that have poor drainage, or where drainage maintenance has been lacking.

Climate and soil type is only the start of blackgrass's ecological niche. Blackgrass was seldom a problem before the 1940s but, because of UK arable farming's subsequent tendency towards winter cropping, reliance on failing herbicides and a mixture of cultivation types that allow the ruderal blackgrass to thrive, the problem has become worse and worse.

As soil type and climate are something that cannot be managed, drainage must be maintained instead. Allowing the free flow of water away from waterlogged and wet areas of fields encourages crops to grow competitively, thus creating more competition for the blackgrass.

Chapter 8 Summary

1. A Martian plant is one that originated in another country or continent. If a Martian plant finds as environment in the new country which fulfils all its requirements with no major predators or threats it can thrive exponentially.
2. Drainage is essential to give the arable crop the best chance to compete against blackgrass.

Chapter 9: The UK dilemma - small fish in a big pond

The UK has the soils and climate to grow the highest yielding wheat in the world and, whilst a constant tussle between New Zealand and the UK for the actual greatest yield of wheat per hectare takes place, the UK average is rarely if ever surpassed. However, it seems there is a constant dilemma and restraint as to why wheat yield increases are being restricted.

9.1 No new chemistry in 20 years, why?

There is an incredibly simple explanation. Most assume that it has become harder and harder to discover new active ingredients as a lot of actives and chemical groups have already been discovered, making it more difficult to find new ones.


Figure 24: Dr 'Dougie' Sammons of Monsanto, St Louis, USA (right) and a chipping machine (left), an incredible machine used in the discovery of the GMO breeding programme.

Dr 'Dougie' Sammons of Monsanto St Louis USA responded….

"Nobody has been looking!" since 1996 when Monsanto launched the first genetically modified organism (GMO) in the USA. Herbicide discovery budgets were slashed by 90% as it seemed glyphosate would be the answer to everyone's weed issues, so why invest in new herbicides? The greatest problem 20 years on is the fact that new herbicides have not been discovered by the major world herbicide manufacturers, but instead by small independent laboratories with highly skilled scientists screening molecules for herbicidal activity. "*When the laboratories closed, we lost a huge skill set from the industry. The industry is only now beginning to relearn what we already knew 20 years ago and that is the reason why herbicides have been so slow to be developed since resistance to glyphosate became a real issue."*

This chain of events has limited the options now available to farmers in the UK.

9.2. Old chemistry still readily available to the rest of the world!

Away from Europe, an older generation of chemicals is still being used far and wide. The names "Atrazine, Simazine, Trifluarin, Gramoxone, Glufosinate-ammonium, Diuron" are still the mainstay of many herbicide programmes where resistance to glyphosate is an issue. Off-patent chemistry like this is also great value and, when mass produced on the generic market, allows commercial crops to be grown with lower input costs.

Figure 25: 1000L of Gramoxone waiting for application in Narrabri NSW Australia.

Figure 26: Chemistry in Shouguang China, measured out and sold by the teaspoon for growers with only 1 Mu (1/15th Ha) to farm

Whilst much of this chemistry has been banned in the EU because there have been cases where it was linked to water course, environmental and operator damage, it is very hard for a UK farmer to compete with a maize grower in China who is able to use Atrazine costing £5 per ha, compared to the £45-£65 per ha that would need to be spent on chemical in our country.

9.3. Sheer scale of agriculture in much of the world!

The USA, Canada, Argentina, Brazil, Russia, Mongolia and Ukraine have quite jaw-droppingly huge agribusinesses, many of which produce two crops and occasionally as many as four crops per year. However such extensification across huge areas of land generally means poorer yields. Still, due to the size of their operations, overall production tonnage per producer is far higher than that of the UK average, which makes them more influential on a world market. Farms and fields that are of this scale are able to operate huge machinery at high speeds and produce high output. Whilst machinery size has no doubt increased in the UK it is ultimately limited to field size and quite often the road or track size leading to it.

Figure 27: A pod of combines at Grupo Bon Futuro Cuiabá Brazil. Growing 440 000Ha of crops (3 a year) comprising soybean, corn and cotton. (With drills following up)

9.4. Low gross margin cereals in 'influential' countries

When it comes to agricultural research and the funds available to carry out this research, the gross margins earned by soybean and corn are the key drivers in the world's most influential agricultural countries and especially in the Americas. Figure 29 (next page) taken over Colorado, shows how wheat is the 'poor relation' and is being grown in-between the irrigated areas of soybean and corn. When looking at product development, the higher value crops are able to 'stand' a higher cost of development and therefore are a more profitable target for chemical manufacturers producing for that market.

Figure 28: Sheer scale of machinery (typical sprayer 3 meter wheel centres)
at the Messina brothers' farm Geraldton Western Australia

Figure 29: Colorado USA - circles showing centre pivot irrigation, dark green soybean, light green corn.
The crop in between the irrigated high value crops is wheat.

9.5. Knowledge transfer

The UK has some of the best agricultural research institutes anywhere in the world. However the transfer of that knowledge from scientist to grower is poor.

The US has an excellent, clearly defined information pathway and this has led to the adoption of similar practices in similar conditions all over the country. Universities lead the research and when papers are published the products are patented. If the products are successful, then the profits are returned to the Universities which results in much of the research becoming self funding. This I found was the case in the Universities of Iowa, Washington State, Texas A&M and Colorado State. In Iowa for instance, seed drills, even if made by different manufacturers, are almost identical on every farm. It's the same for sprayers; the method of nitrogen application by way of injecting anhydrous ammonia; and every farm has auto steer tractors.

Australia leads the world in terms of knowledge transfer and the UK could learn a lot from the great funding supplied by the Grains Research & Development Corporation (GRDC) to projects around Australia. Much of the money is derived from grower levy payments and therefore the grower is not only the funder but also the receiver of the knowledge. The information is written in such a way that it is readily understandable, and is communicated so well too: e.g. through 'WeedSmart' set up by Dr Stephen Powles of the Australian Herbicide Research Initiative (AHRI) based at the University of Western Australia. Dr Powles explained that 25% of the team's budget is spent on communication through Twitter feeds, regular well attended seminars around the country called 'crop updates', and podcasts. More often than not, some of the most influential and innovative farmers – for example Ray Harrington, inventor of the Harrison seed destructor, Lance Turner inventor of the chaff cart for weed seed collection, Rod and Andrew Massina for their controlled windrow and burning - are involved in the communication, which allows knowledge to be explained farmer to farmer using 'farmer language'.

Figure 30: Harrington seed destructor

Figure 31: Chaff cart and elevator. Western Australia

For a summary of Chapter 9 please see over page.

Chapter 9 Summary

1. Research into new herbicides has almost ceased over past 20 years.
2. The EU banned the use of many herbicides, but they are available elsewhere in the world, enabling cheaper crop production costs.
3. Sheer scale of operation gives advantages to much of the rest of the world over the UK
4. Knowledge transfer in UK poor compared to that in many other countries.

Chapter 10: Herbicides - good whilst they lasted

Tepfilo Quispe, a small scale farmer in the village of Huillcapata above Cusco in Peru at an altitude of 12,430 feet above sea level, and successfully growing maize, faba beans, barley, vegetables and flowers, remarked: "*Humans have become addicted to pesticides. The more they use, the more they need*".

Figure 32: Tepgilo Quispe. Peruvian farmer

In some respects this was true until a very recent point in time. Pesticides are a relatively new invention in the timescale of UK agriculture. They, together with fertiliser and plant breeding led to the incredible agricultural revolution during the middle to late 20th century when yields rose exponentially. Much of this revolution has now been negated because of the lack of herbicides for blackgrass control.

10.1. Plenty of options

By the 1970s blackgrass was infesting a high percentage of the UK's intensive combinable crop areas. Yet in the mid to late 1970s blackgrass wasn't so much of a problem. This was in no small part due to the effective ways in which herbicides managed the weed so effectively then. I am referring to

Dicurane, Isoproturon, Hoegrass, Commando, Stomp, Treflan, Hawk, Cheetah, Lexus and finally Atlantis. These herbicides were all 'in crop' herbicides and were effective at keeping blackgrass at bay whilst the cereal crop was planted at its optimum time of circa 25th September at low seed rates. This allowed effective tillering and provided reliable yields. Combined with 'in crop' herbicides there were also the 'out of crop' herbicides which were used as a pre-planting clean up before crops were drilled. E.g. Paraquat, glyphosate and Glufosinate Ammonium.

A combination of herbicide bans due to water pollution, operator safety or environmental fears, together with the increase in herbicide resistance by blackgrass has led to resistance to all herbicides except one. The exception is glyphosate – or at least for now.

10.2. Chemical groups

The world uses 3 different herbicide classification systems:

1. The WSSA (Weed Science Company of America) system used only in the US and Canada
2. Australia has its own system based on letters and used only in that country. Herbicides are grouped by letter (A-Z) according to type
3. The rest of the world uses HRAC (Herbicide Resistance Action Committee) classification. HRAC is an international body founded by the agro-chemical industry

Figure 33: Clearly labelled chemical groups located on chemical cans. Australia (HRAC)

If the grower knows and understands that their weeds are resistant to a particular chemical group then, depending on resistance type, target site or enhanced metabolism, a correct decision can be made whether to use that group at all and, if so, its appropriate dose rate. Herbicide *mixtures* contain different active ingredient groups as part of a strategy to prevent resistance buildup.

10.3 Glyphosate

Glyphosate was described by Dr Stephen Powles (University of Western Australia) as a once-in-a-lifetime discovery, and yet resistance to it was a challenge in so many of the countries visited. When asking various scientists about the likelihood of glyphosate-resistant blackgrass occurring, the replies were quite chilling. Dr Pieterson of the University of Stellenbosh (South Africa) replied: "*It's not a matter of if, it's a matter of when. Good husbandry could delay it for many years, even decades.*" Dr Michael Owen of Iowa State University (USA) replied "*Glyphosate resistance prevention is quite simple. Do not repeat what we have done in the USA, Canada, Brazil, Argentina and Australia, i.e. multiple applications of glyphosate with no mechanical tillage.*"

Figure 34: Dr Michael Owen of Iowa State University (USA) (red shirt)

When describing the UK's current trend towards no-tillage agriculture and the use of stale seedbeds, Dr Michael Walsh (University of Sydney, Australia) replied: "*Einstein described insanity as, doing the same things over and over again and expecting different results.*" That remark went against the conservation agricultural techniques currently taking over parts of the UK arable sector.

Blackgrass's tolerance and resistance to glyphosate in the UK is somewhat confusing. Current work being carried out by research at Rothamsted adds support to the figure below, published in 2012, showing a definite increase in the ability of blackgrass to survive glyphosate applications. This is an alarming trend which requires serious consideration across the industry. If a no-till system is being considered there must be regard for how to remove glyphosate tolerant/resistant blackgrass survivors.

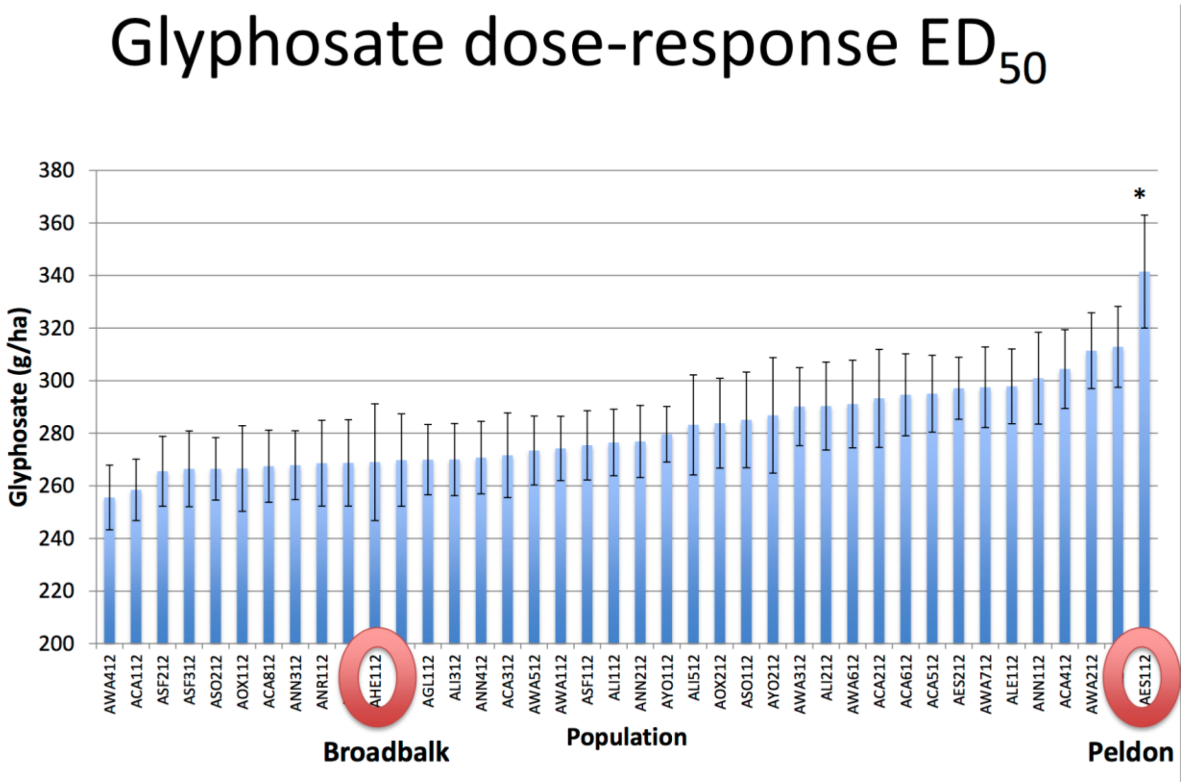

Figure 35: Amount of glyphosate needed to kill blackgrass in the UK. (Source Rothamsted Research 2012)

Please see also : http://www.ewrs.org/herbicide_resistance/doc/023_Davies.pdf

10.4. Anything new?

As discussed in Chapter 9, very little in the way of new herbicides is available. Yet across the world there are a few indications that new chemistry with a 'novel' mode of action is being developed e.g. current use in cereals, pulses and oilseed rape of FMC (F9600). These look very exciting on AL- resistant blackgrass, and only time will tell when they are brought to market.

When new products are brought to market with a wide range of projected application they must be used responsibly. A new chemical shouldn't be used every year, and certainly shouldn't have its rate of application cut. Instead its use should be in mixtures with other active ingredients to prevent resistance. This of course is obvious so why are such statements being ignored when it comes to the use of glyphosate?

The Grains Research and Development Council in Australia has sponsored 4 PhD students to visit the major herbicide manufacturers of the world and study old catalogues to try and determine if any products or modes of actions were overlooked or missed during their development phase. It seems, at least in the short term, that very few options for 'magic in can' are being developed. This might change as herbicide research and investment is increased. Total reliance on herbicides in the future would be avoided if current knowledge that weed resistance to them is just around the corner was accepted, necessitating adoption of an integrated approach to weed control.

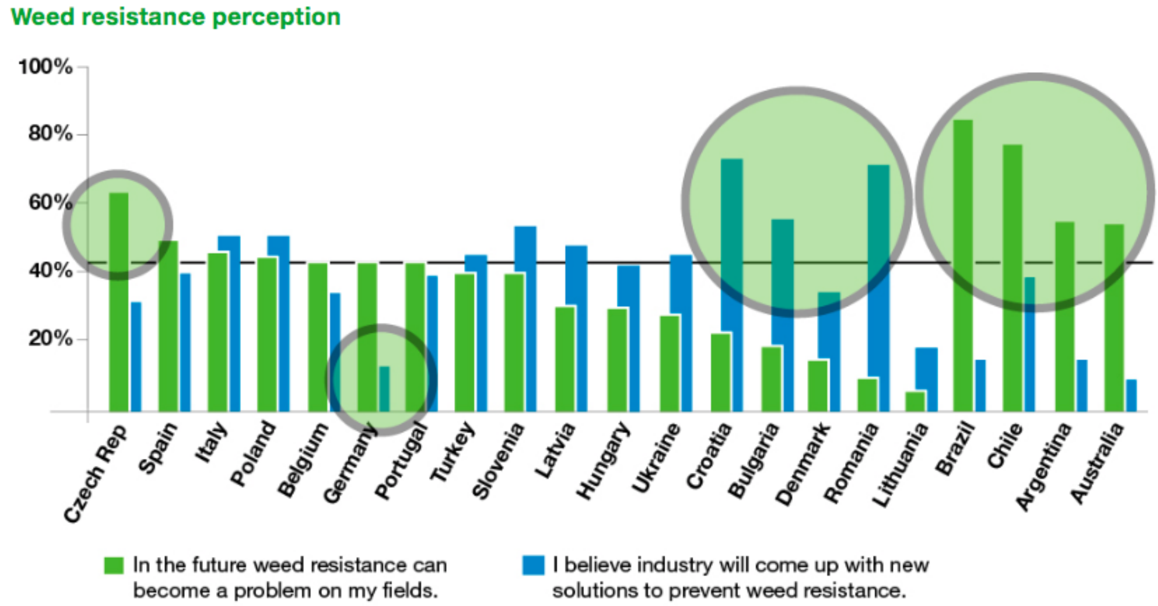

Figure 36: Perceptions of weed resistance. Source: Bayer Crop Sciences

Figure 32 above demonstrates two things:

1. The countries with the best knowledge transfer and support between scientists, growers and agronomists - such as in Germany, Brazil, Chile, Argentina and Australia - realise that the industry will not come up with solutions fast enough yet, all the while, the issue of weed resistance is becoming worse.
2. In the countries where knowledge transfer is not as developed - such as Croatia, Bulgaria and Romania - the opposite is the case. Sadly the UK's situation is more in keeping with this group, and needs to change.

Chapter 10 Summary

1. Much of the incredible arable revolution in the mid to late 20th century has now been negated because of lack of herbicides for blackgrass control
2. Many herbicides have been banned by the EU in recent years.
3. Glyphosate resistance is inevitable.

Chapter 11: GMOs - pressurising the system

Possibly the most contentious issue with regards to world cropping is the political challenge of GMO acceptance or otherwise. Of the countries I visited in 2016-2017 Argentina seemed the most pro-GMO. Some of the first commercial GMO-crops were grown there, and a huge research programme introduced many new traits to the main crops of soybean and corn. A soybean crop visited was at the current cutting edge of GMO technology and had nine stacked GMO traits located within it. These traits were for 4 herbicides and 5 Insect-resistant genes. The herbicide resistance was for glyphosate, glufosinate ammonia, Dicamba and 24D (targeted mainly for herbicide resistant broad leaved weeds rather than grass weeds).

Figure 37: GMO trials in Montana

11.1. GMOs around the world

Of the countries I visited, the one most opposed to the adoption of GMO technology (other than the UK and vast parts of Europe) was Russia. In July 2016, Vladimir Putin banned the cultivation and breeding of GMOs except in cases where needed in testing and scientific research. This makes Russia the world's largest GMO-free territory. This decision by the Russian government was influenced by environmental organisations, farmers and other representatives of Russian society, concerned by the absence of reliable scientific studies on the long-term risks of GMO foods to human health and the environment. The decision also took into consideration the interests of national food security, as the world market of genetically modified (GM) seeds is monopolised almost exclusively by American, German and Swiss-based companies.

The most 'confused' countries in terms of attitude to GMOs were China and Australia. Each has individual provinces (South Australia and Heilongjiang province) that have totally banned the growing of GMO whilst much of the rest of each country doesn't have such *blanket* restriction. Instead restrictions have been imposed relating to individual crops. In China, for instance, only cotton and papaya were allowed to be GMO.

Many Americans and South Americans found the UK's GMO policy amusing. The UK has a total ban on the growing of GMO seeds, but allows the import of many products of GMO origin. Soybean and corn make up the vast majority of such imports; cotton, sugar beet, and oilseed rape and their products are also permitted.

As plant resistance to one herbicide becomes more and more widespread the obvious route of research would be in the development of a new herbicide. But as discussed in chapter 9, this is proving difficult because of loss of knowledge base. One knowledge base that *has* increased is that relating to GMOs. Monsanto has discovered "seed chipping technology" which enables testing before the seed is even planted, effectively reducing the time it takes to produce a new variety by more than two years. The next result is to allow herbicides to be used in crops that would have previously been killed by using that particular chemical.

11.2. GMOs in the UK?

Despite a glyphosate-resistant strain of wheat being developed by Monsanto, when this was only months away from general release it was decided for commercial reasons not to launch it. That leaves only three commercially grown crops in the UK that *could* employ currently available GMO technology with regards to herbicide tolerance. These are sugar beet, maize (corn) and oilseed rape. GMO seed for these crops is commercially available throughout the world and all with resistance either to glyphosate or glufosinate ammonia. Glufosinate ammonia, however, is not available for use in the UK, so 'in crop' glyphosate is left as the only viable GMO herbicide available which might aid the control of blackgrass in our country.

As discussed earlier, the biggest problem with GMOs is complacency. Introduced in the mid 1990s, the development of no-till drilling came about because any hitherto herbicide-resistant weeds could then be controlled in the crop by glyphosate (which was newly on the market), and would not require any mechanical weeding. This led to the rapid development of glyphosate resistance. The herbicide that was deemed unbreakable simply broke and surprised the entire industry. Continual exposure of weeds to a single herbicide, with absolutely no other herbicide or mechanical weeding, meant that a mutant of a weed species could soon multiply and become an issue. This is exactly what happened and is continuing to happen.

Conservation agriculture is a real trend throughout the UK. No-till drilling is being practised and therefore any plants that are herbicide resistant are not being removed mechanically either. In the USA, the Petzenhauser family in Iowa had been practising no-till drilling and the growing of GM soybean and corn for many years. However the huge increase in glyphosate resistant weeds has led them to invest in an inter-row cultivator to remove any glyphosate resistant weeds. This prevents the weeds from going to seed and therefore multiplying. This practice is being repeated across many parts of the world and shows how important mechanical weeding is as a tool for fighting weed resistance.

Figure 38: 3 photos of the Petzenhauser family in Iowa, who, despite having grown many GMO crops have invested in an inter row cultivator to help with their glyphosate resistant weeds.

See also the photograph below.

I feel that the combination of conservation agriculture (no-till), which is totally dependent on glyphosate to make it viable, plus the use of more glysophate 'in crop', simply replicates the conditions that have led to the glyphosate resistance issues in the rest of the world.

Einstein has been quoted earlier in this report as defining insanity: "Doing the same things over and over again and expecting different results."

Chapter 11 Summary

1. **No-till, plus too much reliance on glyphosate, will lead to the widespread development of glyphosate resistant blackgrass in the UK.**

Chapter 12: Cover crops - the answer to everything!

The current trend in UK arable farming goes hand in hand with conservation agriculture. It involves the growing of cover crops. The theory is that cover crops prevent soil erosion, increase soil organic matter, dry soils out, maintain nutrition, prevent weed emergence and increase microbial activity in the soil.

On my study tour opinions about cover crops were diverse. In Argentina, Martin Lahitte of the 110,000Ha farm El Silencio, part of the Bellamar empire, cover crops were not being employed, because of the difficulty of establishment due to cooler weather. However, Martin explained that cover crops would be very useful because they would suppress the growth of weeds during the fallow period. This would mean no weed problem needing to be controlled prior to planting, thus putting more strain on the glyphosate resistance issue. In Australia, cover crops were not used due to the lack of moisture, and in a climate that often produced a maximum rainfall of 300mm cover crops could simply not be supported.

Figure 39: Discussing ways to improve wheat growing with the author. Mr Yan Guolin Farmer in Jiaxing (black coat). Mr Yifan 'Ivan' Xu Interpreter (purple coat). Mr Yen Uling Zhejiang AMP (blue coat)

In China's Jiaxing province, Mr Yan Guolin farming 370 Mu (very large farm in this area with 362 individual landlords!), discussions centred around cover crops on the paddy fields left all winter. Mr

Yan Guolin found that cover crops can cause disease carry over. They are hard to establish in the late autumn and rarely seem to improve the situation. Despite this an experimental field of wheat had been planted to see if it was useful as a cover crop and if it could be taken to harvest prior to the rice being planted, potentially doubling income.

12.1. Establishment of cover crops

The problem facing most growers around the world seems the same as in the UK: establishment. Establishment has two problems:

Firstly the crop needs establishing as early as possible in the autumn. This is a time of year when there is so much to do and seeding of cover crops can be neglected because other farm operations take priority.

Secondly, establishment issues. Soil texture is so important. Whilst it is easier to establish a cover crop on soils that contain little or no clay >30%, some soils that desperately need restructuring or the soil organic matter increasing have clay contents, often >80%, and rapidly become waterlogged in the autumn. This prevents good establishment and it is therefore hard for the cover crop to do the job it was intended for.

12.2. Weed control in cover crops

Whilst glyphosate resistance is a huge problem around the world and cover crops can compete with resistant weeds during a fallow period, in the UK the greatest and possibly only opportunity to clean up as much blackgrass as possible is following harvest of the previous crop and before establishment of the next crop. This is achieved by using the stale seedbed technique, where blackgrass is encouraged to grow, dependent on weather conditions, and each subsequent flush of blackgrass is removed by either an application of glyphosate or by tillage.

12.3. Cost of cover crops

The cost of some of the cover crop seed mixtures introduced into the UK needs huge justification in terms of the benefit derived. Interestingly AHDB has recently conducted a survey of their monitor farms and, of the 7 interviewed, 6 had not seen an increase in either yield or net margin following the use of the cover crop, and the improvement in soil structure lay in perception rather than a measurable unit.

12.4. Seed mixes

Many of the cover crops prescribed to be grown in the UK are of “Martian origin” - whether it’s Egyptian clover or black oats. There are two issues with importing seeds from around the world. Firstly if the plant happens to find its ecological niche in the UK, there is a possibility that it may become a problem in its own right. Secondly, black oats have origins in the Mediterranean region and weeds from that region, as already outlined, are a huge problem in the UK … viz blackgrass!

12.5. Increase microbial activity?

Undoubtedly there is an increase in microbial activity when any roots or plant material are introduced into the soil. The problem of course is the assumption that all microbial activity is positive for the soil, when in fact, as Dr Anne Kennedy (University of Washington State) explained, the current understanding is that there are as many microbes in the soil that are non-beneficial as those that *are* beneficial. These microbes are so site-specific that the idea that soil health can be measured is doubtful. As demonstrated by the #soilmyundies experiment, where cotton (bleached white) underpants are buried in differing cultivated soils to prove that the most rotted pants denote the most healthy soils, anything that causes rotting in the soil could also lead to rotting of the very plant roots that the farmer is trying to establish.

12.6. Soil moisture?

An interesting theory with regard to cover crops is that they dry out the soil. When discussing this issue with Professor Bhagirath, Singh Chauhan (University of Queensland, Australia, who is incredibly knowledgeable about both Australian and Asian cropping systems) his first response to the drying soils concept was: "*What if it rains*?" - a fair question when living in a maritime climate. He went on to describe how a cover crop could actually do the opposite of desiccation as they create their own micro-climates.

A part of a field on a farm at Kings Sutton, Banbury, UK, had been drilled with a mustard cover crop to dry the soil out, and the rest of the field had been planted as spring barley. The following oilseed rape crop was directly drilled through the two previous "crops" (Figure 40) with the cover crop producing a far wetter soil, less friable, requiring more horsepower to pull the drill through it causing increased wheel slip and therefore less efficiency.

See figure 40 on next page

Figure 40: Cover crops 'holding' moisture in the soil. Kings Sutton, Oxfordshire

Figure 41: Slug problems where fodder radish was established. Claydon. Oxfordshire

12.7. Soil pests?

Following an excellent crop of fodder radish that was also used as a holding crop for game birds, the gamekeeper mowed a curved feed ride through the crop on which to feed the pheasants and partridge. The crop was left over-winter and planted in the spring with oats. Figure 41 demonstrates the devastating effect caused by slugs in the main part of the field, but how in the ride mowed through the fodder radish the oats are growing away with little slug activity.

12.8. Nutrient holding capacity?

Waterlogging causes denitrification by anaerobic bacteria. By growing cover crops to improve soil structure and drainage, the soils eventually become better structured and therefore prevent denitrification. Many cover crops contain vetch or pulses which have the ability to 'fix' atmospheric nitrogen into the soil. The problem with vetch and pulses is that they have very little if any aerenchyma and therefore do not survive in the waterlogged soils that the farmer is trying to rectify. As discussed before, there is no aerenchyma in brassica crops either. This confirms that fodder radish, with its deep rooting potential, will not help structure in the more waterlogged soils that are being targeted and can actually produce ethylene which can cause problems to the following crops.

12.9. Selection of yet another emerging timing?

As discussed in Chapter 7, the 'levelling' of peaks in blackgrass emergence (Figures 19 and 20 in Chapters 7.2 and 7.3) will hinder the control of blackgrass. Oilseed rape encourages blackgrass germination in late August, cover crops encourage it in September, barley in October and wheat in November. This cropping, combined with a varied array of spring crops will actually flatten the blackgrass emergence graph even faster. The lowest blackgrass pressure found in a crop is following a tall spike of blackgrass emergence - and therefore cover crops will only lead to future problems.

12.10. Residual herbicides

The effectiveness of residual herbicides is dependent on many factors. Firstly in order for the herbicide to work it must be in a place where it can - the soil surface. Work carried out by the AHRI, GRDC and UBA has shown that interception by stubble, green manures, straw and trash can intercept up to 70% of the applied residual herbicide. Furthermore, if the material that intercepts the herbicide is moist, the latter is less likely to wash off into the soil following a further rain event (*Yaseen Khalil*). When the herbicide does reach the soil surface the solubility and ability to attach to the soil and microbiological activity all have a huge impact on how effective the herbicide actually is.

The catonic exchange capacity (CEC) increases in line with the level of organic matter in the soil, locking up the herbicide and rendering it ineffective. As cover crops are being used to increase soil organic matter this could ultimately lead to problems.

The half-life of the herbicide (the time it takes for the herbicide to deplete by half in the environment) is based around microbial activity i.e. the more active the soil microbes, the less the half-life of the herbicide and therefore the less effective it will be over time. Work carried out in India by Gupta S. Gajbhiye VT on Flufenacet (Flufenacet is an oxyacetanilide herbicide applied before crops have emerged) has shown that where the half-life is quoted as 40 days on the label, high levels of microbial activity can reduce this to 10!

Of course, in the USA, Canada, Brazil and Argentina, where GMO seeds are most widely used, the use of contact herbicides means that the reliance on residual herbicides is not required and therefore cover crops can increase the soil organic matter content and microbial activity without any adverse effects.

12.11. Blackgrass - the ultimate cover crop?

A plant that requires no financial investment, requires little if any establishment costs, establishes well in the wetter parts of the fields and therefore has maximum impact in the wettest areas, does not attract slugs and has the ability through its aerenchyma to oxygenate waterlogged soils which prevents denitrification …. it's hard to argue that blackgrass is not actually the perfect cover crop!

Chapter 12 Summary

1. Attitudes in the rest of the world are ambivalent towards cover cropping.
2. In many circumstances cover crops in the UK are proving to provide more challenges than they are solving.

Chapter 13: Using biology - beneficial bacteria

So much is being talked of with soil health, cover crops and microbial activity, that a visit to Dr Anne Kennedy at the University of Washington State supplied some interesting information from her 40 years of work specialising in this field.

Figure 42: Dr Anne Kennedy (University of Washington State, USA)

Anne was enthusiastic about sharing her findings which I believe could have implications the world over. Anne began by showing me a photograph of a wheat field from Washington State that had an obvious problem. Was it pH? compaction? waterlogging? disease? pest?

No, she said, it was: "*Bacteria and microbes*." Anne explained that she had identified bacteria that inhibit the growth of wheat in Washington State. They were only present in small numbers and reduced as the soil warmed up in the early spring as the wheat began to grow away. Anne explained her journey when she theorised that if the bacteria attacked the wheat roots or seed then they must affect the weed seed.

Cheatgrass *bromus tectorum* (a Martian species) is one of the largest agricultural weed problems in Washington State and is invasive in natural grasslands. In summer, cheatgrass creates huge problems when it senesces (deterioration with age) and becomes a fire hazard across the open prairie lands. Anne's breakthrough came after screening 25,000 naturally occurring soil bacteria from the local area. She isolated a bacteria she named D7, a bacteria that would feed on the early growing roots of the cheatgrass and prevent it from gathering enough nutrition to enable the hypocotyl (the stem of a germinating seedling, found below the cotyledons and above the radicle) to grow. Further research also led to the identification of the latest bacteria that not only attacks cheatgrass, but also jointed goatgrass (*Aegilops cylindrica*) and Medusa head (*Taeniatherum caput-medusae*), codenamed ACK55.

Results of its effect on the three weed species were quite dramatic! The genetic stability of the bacteria is important and the fact it is naturally occurring in the soil means it is not an introduced or "Martian" species.

Figure 43: Left D7 a huge reduction in viable cheatgrass seed within five years

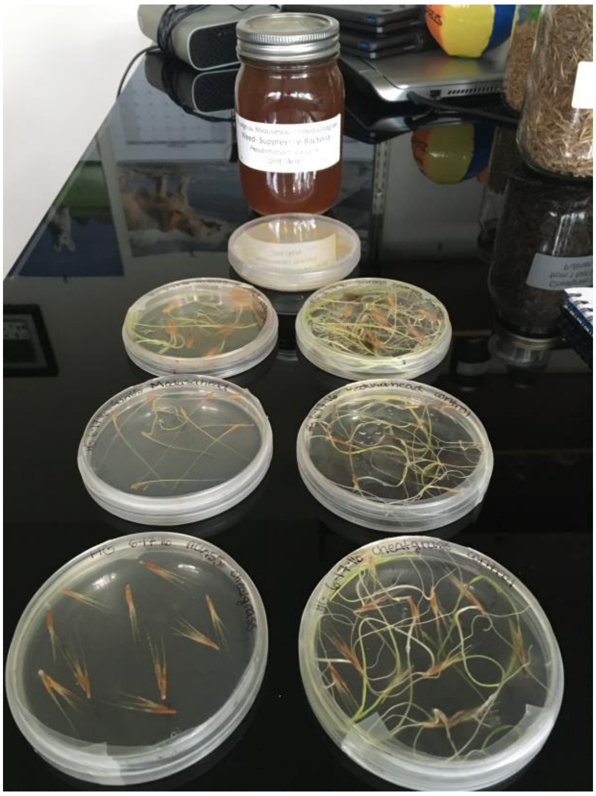

Figure 44: ACK55 showing effect on cheatgrass, Medusa head and jointed goat grass.

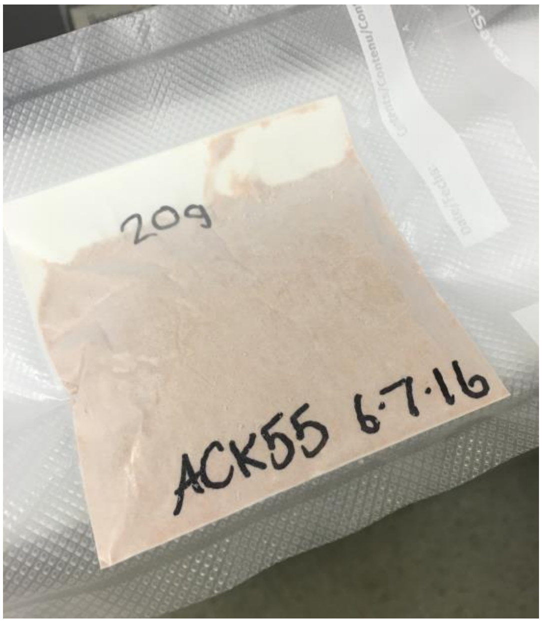

Figure 45: ACK55 freeze dried, applied in late autumn at 20g per acre

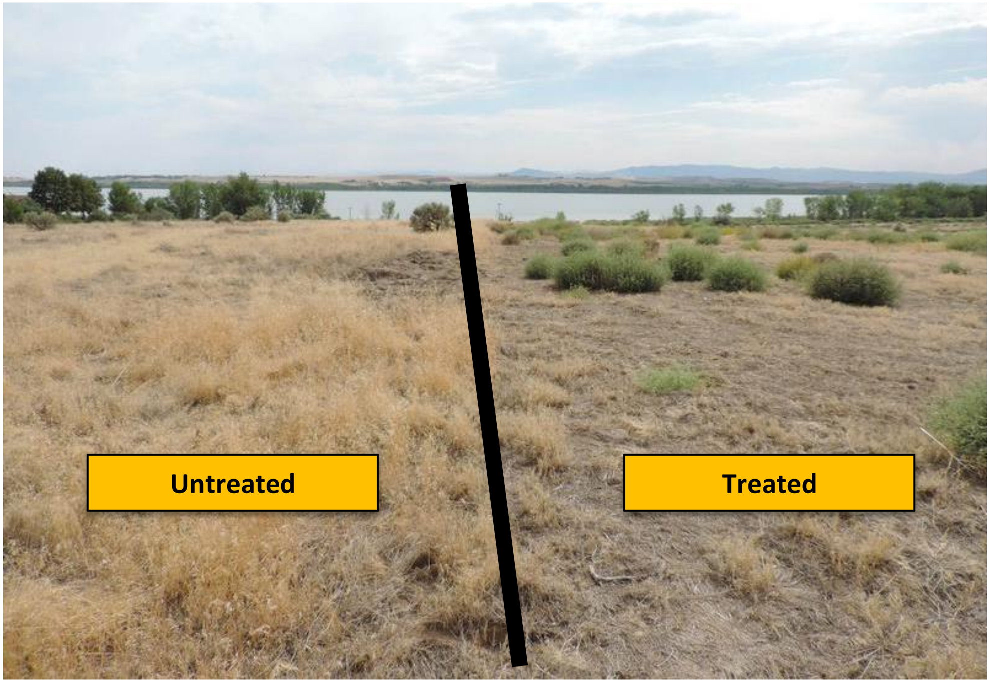

Figure 46: Cheatgrass control, five years after application

Anne is now looking at UK soil bacteria and blackgrass seeds. Results are due in the near future.

Chapter 13 Summary

1. Natural microbes found with the soil can be multiplied to reduce the weed seed bank
2. Crop growth can also be inhibited by soil bacteria and microbes

Chapter 14: Cultivations - the pressure release valve

"We plough the fields and scatter" said *Matthias Claudius in 1777* and, despite the tribulations of the infamous Bettinson direct drill in the late 1970s and early 1980s, this practice continued unhindered until the turn of this century. Then glyphosate was used as a tool for weed control and particularly where, as farm sizes increased and labour availability decreased, it was proving more and more difficult to obtain a good enough quality seedbed on soils with high clay content.

Ploughing is now seen by many as a total non-option for use on their farms, despite the research showing a mean average of 69% weed control. (In fact control ranges from -88% to 96%.) The range is indeed exceptionally wide and investigation is needed to understand if there are abnormalities in the research and/or what caused the huge fluctuations in results.

14.1. Cultivation history

Cultivations were historically designed to give the crop being planted an ideal establishment compared to that of its weed competitors. They were also used to kill the weeds present, remove disease build up and expose certain pests that could be predated on. When blackgrass began to become a national issue in the late 1970s, these cultivations caused selection for blackgrass mutants that enjoyed vigorously tilled land. This blackgrass mutant was sprayed off with glyphosate and then the crop was established - usually with a power harrow combination drill that yet again greatly disturbed the soil.

Figure 47: The power harrow combination, a farm favourite during the 1970s, 80s, 90s and well into the 2000s. Maximum soil disturbance by mechanical stirring.

As in-crop herbicides began to fail, glyphosate became a more important tool in the arable rotation and the stale (or false) seedbed became important, creating a seedbed in which the blackgrass would establish well, was sprayed with glyphosate, and then the crop would be drilled. The disturbance caused by drilling the crop, however, meant another flush of blackgrass would come through with the growing crop, and poor control from herbicides meant these plants would set seed.

Figure 48: Ideal stale seedbed, showing a huge blackgrass flush ready to be sprayed with glyphosate prior to planting winter wheat. Warwickshire, UK

So low or no disturbance drilling was the next step considered in blackgrass control. Cultivations to create a stale seedbed, then remove the germinated blackgrass with an application of glyphosate, following that with a low disturbance tine or disc in which to plant the crop, were similar to those adopted across the rest of the world. Dick Neale of Hutchinsons, in combination with Cousins machinery manufacturers, developed one of the first UK-designed low disturbance oilseed rape drill and proved the theory to be correct with very little blackgrass emerging in the undisturbed soil between the rows of oilseed rape.

During this time, the delayed drilling option was also studied. This was mainly for two reasons: firstly the more stale seedbeds that could be created before a winter wheat crop was grown, the less blackgrass seed there would be to compete with the winter wheat. Secondly the delayed drilling would follow the peak germination timing for blackgrass and therefore also lead to a reduction in blackgrass competition in the growing crop. However fields selected for the stale seedbed technique were often those with the highest clay content on each individual farm. In a wet autumn waterlogging could cause a problem and either prevent disc drills working at all, or cause the slits they drill through to become clogged up or, worse still, not allow the crop to be drilled at all.

Figure 49: Minimum disturbance disc drill used in San Jose Uruguay - used the world over in no tillage agriculture and fast becoming popular in the UK.

The final step in the cultivation timeline has been to eradicate it completely. This has been commonly referred to in the UK as 'conservation agriculture' and been alluded to in many chapters in this report. The low or no disturbance would prevent any further blackgrass from germinating during the growing of the crop, and blackgrass at depth would decline due to the microbial activity (blackgrass declines 70% per year when buried at a depth below 50mm. *Stephen Moss*). Any blackgrass that emerged between crops would be eradicated using glyphosate and in-crop the small amount present would be controlled by herbicides that continued to have activity on the blackgrass. However ……

14.2. Tillage selection

The biggest problem involved in the shift to fewer and fewer cultivations is the lack of acknowledgement of blackgrass's ability to adapt. Blackgrass thrives in cultivated land only because it has self-selected to do so. Decades of continuous plough-and-power-harrow-drill combination created blackgrass mutations that would be triggered to germinate when the soil had been tilled. This of course could soon change when mutations begin to create blackgrass that doesn't require soil disturbance in order to germinate. In time blackgrass will adapt to non-disturbance tillage.

This lack of acknowledgement is also a problem for delayed drilling. Yet again historical planting dates for winter cereals and winter oilseed rape have led to huge selection pressure on blackgrass to germinate when the crops were being "ideally" established between the end of August and the first week of October. Delaying drilling in the first instances would provide excellent results because most of the blackgrass would have germinated prior to the crop and been eradicated. However, the more drilling is delayed, the more mutations of blackgrass for later emergence occur, and eventually this will lead to blackgrass naturally emerging in November/December.

Figure 50: Intensive application of no-till drilling in Warwickshire

Intensive application of no-till drilling in Warwickshire has seen a rapid increase in blackgrass adapted to no-disturbance conditions.

In the photo above note the blackgrass between the rows of undisturbed ground compared with the disturbed ground - a complete change around in blackgrass properties has taken place in 9 years.

Chapter 11, which discussed GMOs, highlighted the potential problems that heading down the conservation agriculture route presented for the UK. Whilst no-tillage has environmental benefits, it relies solely on the use of glyphosate as its method of blackgrass control. This heaps huge pressure on the use of glyphosate as a herbicide, much like the pressure that caused in-crop herbicide resistance to develop historically.

14.3. Ploughing an essential tool

Ploughing is very much a lost art. Due to lack of knowledge, the plough is often misunderstood and therefore ignored.

> *"Where it is used it is seldom set up correctly and many commercial ploughs are used in such a way that they cause more problems than they are trying to solve."* (John Rogers, Trumpet Society ploughing judge)

> *"The speed of commercial ploughing often throws soil from one skimmer onto the top of the adjacent furrow, rather than the bottom of the furrow where it should be placed neatly. Furrow widths are set as wide as possible as a means to cover more ground faster. Skimmer discs are often not installed on the plough which prevents a clean cut, and lastly the plough is usually set to a depth far below that of where it should be, 15cm was plenty deep enough for a horse plough, the soil texture hasn't changed?" (Jack Merchant, New House Farm, Abergavenny)*

It seems obvious then why the variation in weed control of between -88% to 96% has been measured (see second paragraph of this Chapter 14). It's not so much about the variation of the results but much more a result of how you plough!

Figure 51: "Correct plough settings make all the difference to weed control"
Jack Merchant, ploughman, New House Farm. Abergavenny

14.4. Surface tillage

Surface tillage is also a vital tool in the fight against blackgrass. Mechanical removal of weeds that are resistant to herbicides will prevent these weeds from producing seed. This is especially important in the management and prevention of glyphosate resistance.

> *"Straw harrows, more commonly known as stubble rakes, are a very fast way of mechanically removing a lot of blackgrass seedlings during a busy period, especially because of the widths available (15m) and forward speeds of up to 30Kph, a vital part to play in an anti-resistant strategy" (Geoff Claydon, Claydon Drills UK).*

> *"In order for a straw harrow to work effectively in hard ground following harvest, the ground would be ideally surface-cultivated which moves only the top 50mm of soil, but across the whole soil surface. This allows easier penetration of subsequent rakes and better removal of blackgrass seedlings." (Richard Tustain, Chacombe Lodge Farm, Oxfordshire UK)*

14.5. Inter row cultivation

Inter row cultivation is also possible with wider row spacings found on many strip-till drills due to robotics. Specialising in row crop equipment, Philip Garford said:

> *"Garford is a world leader for their range of Robocrop Precision Guided Hoes and Robocrop InRow Weeders. The Robocrop range of products use video cameras and image analysis computers to locate crop position and then guide the hoes quickly and accurately". (Philip Garford at 'Mechanical Weeding live' Cirencester).*

Figure 52: "*Stubble raking is an important part of an integrated approach to remove herbicide resistant blackgrass*" Richard Tustian, Banbury. Oxfordshire

Peter Newman (University of Sydney) is also developing 'targeted tillage' where instead of a squirt of glyphosate being applied to a weed on an individual basis, a mechanical hoe is released into the soil to mechanically remove individual weeds. It is therefore vital to continue with mechanical weeding in the UK as a way to prevent glyphosate resistance and further resistance to other herbicides.

However, it must be acknowledged that if a cultivation method is used and repeated for each and every crop year after year, blackgrass will mutate and become adapted to the new environment.

Figure 53: Robocrop guided hoe as demonstrated by George Hall, at Mechanical Weeding Live (Rural Innovations Centre, RAU Cirencester)

Chapter 14 Summary

1. The past 10 years have seen a continued shift away from deep cultivations to a shallow cultivation system and using glyphosate to kill off blackgrass in stale seedbeds
2. Crops are then drilled with minimum disturbance equipment
3. There is a movement in the UK to eradicate cultivations completely
4. In time blackgrass will adapt to both non-disturbance and delayed drilling
5. Mechanical weeding is essential to control blackgrass that has survived herbicide applications (in particular glyphosate).

Chapter 15: Discussion: is BEN the answer?

Weed management throughout the world has brought many new ideas and concepts. For the most part, weeds that become the greatest problems for any country are "Martian plants" introduced either by error (Johnson grass in Argentina) or on purpose (ryegrass sown for sheep paddocks in Australia). They have then gone on to find their 'ecological niche'. These weeds, as with all living organisms, have the ability to adapt to a changing environment and can either be naturally selected or artificially selected by mutant strains of the same organism adapting better to the environment and therefore becoming established as the new strain of that species. Plants that, like blackgrass, are annual weeds are able to select and change their populations quickly because they produce new offspring each and every year.

Blackgrass has found its **ecological niche** in the UK due to our wetter maritime climate which favours blackgrass's growth and reproduction; and also, because of aerenchyma found in the roots, it is able to survive for longer in waterlogged conditions. These soil conditions have become more prevalent in the UK for two main reasons: with the end of grant aid for drainage in the 1980s, field drains which are generally given a life expectancy of 30 years have now become inefficient - and many drains were installed decades before that. Constant ploughing and power harrowing, in many instances, has removed much of the accumulated soil organic matter and completely removed soil structure, both of which contribute to good field drainage.

Whilst some **new chemistry** seems to be in development, the thought that this will solve all problems in the future is futile. **Correct management and integration of different methods** need to be used wherever possible to prevent the rapid buildup to resistance; despite the fact they may only be a delaying tactic they should still be employed. **Glyphosate resistance** is of huge concern to the UK and the introduction of GMOs will only increase the already huge pressure on the amount of exposure blackgrass has to the chemical.

Tillage should still have a huge place in UK agriculture, whether it is ploughing to reset the system, surface cultivating, stubble raking or inter row hoeing. The importance must not be underestimated as part of a system to prevent glyphosate resistance by mechanically removing any survivors. Conservation agriculture may seem a good idea, but lessons need to be learnt from the rest of the world.

Whilst **cover crops** aim to increase soil organic matter and improve drainage, which would eventually lead to better established crops and a less favourable environment for blackgrass to thrive in, blackgrass will in fact grow equally well in well-structured and freely draining soils. If blackgrass is the main concern for the field, eradication by producing stale seedbeds and stubble raking them is most effective with a single dose of glyphosate pre-planting. If cover crops are required then it is hard to argue that blackgrass doesn't in itself provide the ideal solution.

Biological control could have a place where it could go on working quietly on the seed bank year after year. Bacteria identified for doing this must have ecological stability and be unable to mutate much like ACK55.

With all this in mind it is hard to argue against changing to a farming system that, rather than fighting against natural pressures, actually works with them, and also has the benefit of helping the control of blackgrass. This however involves looking at rotations in a completely different light and making artificial selection to benefit the farmer rather than the blackgrass. It was because of selection pressure that delayed-autumn-drilled, or spring-drilled, crops were so clean from blackgrass, following previous decades of selection during which wheat/oilseed rape rotations had a very narrow drilling window (late August to late September planted). Delayed drilling and spring drilling are beginning to produce more blackgrass because of selection pressures and the 'levelling out of the emerging pattern graph' (see chapter 4).

The exact same thing has happened with cultivations: constant ploughing and soil disturbance created blackgrass mutants that liked disturbed soils. When employing no-till drilling the system seemed to have solved the problem. However those leading the no-till drill revolution have started to come under real pressure and, in a winter oilseed rape crop in Warwickshire, non-disturbance blackgrass has self-selected because of a 9 year repetition of the technique.

Desperation often leads to innovation and no more so than the case in Australia where the first herbicide-resistant ryegrass was identified in South Australia in 1982 and quickly spread nationwide. Different herbicides were used until a ryegrass plant had developed resistance to seven different modes of action herbicides (group 1, 2, 3, 8, 13, 15 & 23). Growers like Lance Turner, Ray Harrington and Rod Messina became innovators, creating solutions beyond herbicide that can help to win the battle against ryegrass. These inventions (windrow burning, chaff carts and seed destructor) were quickly admired by the scientists working on ryegrass resistance. They began working together to help solve the problem. Once developed the knowledge gained was then shared systematically across the country and widely adopted.

Unfortunately their solutions do not aid blackgrass management in the UK as the blackgrass seed is shed from most of the heads pre-harvest whereas in Australia ryegrass seed remains in the head. However even if this was the case for blackgrass, windrow burning is not allowed in the UK. Chaff carts (used in Australia) would also need emptying every few hundred meters in the UK because of the density of the crop and the seed destructor would be overfed by the quantity of chaff and seed falling into it, so that forward speed would be ineffective.

No matter what herbicides are in the development pipeline, herbicide resistance is just around the corner and an integrated approach to blackgrass control must be taken. Plants that have established themselves in a "Martian" environment and have found their ecological niche become extremely damaging and difficult to control.

Innovation is important, but needs backing up with understandable theory. Ideas that work combine the facts that:

1. Blackgrass is now a naturally occurring cover crop
2. Develop Darwin's theory of selection to work with nature
3. Then use an artificial neutralizing method to restart the process

This is far more logical than the current approach in the UK of allowing self- selection by this "non-native" plant (blackgrass) that is able to germinate all year round, under any cultivation methods and in any crop!

15.1. BEN system to aid the management of blackgrass

My study tour has enabled me to devise a new strategy to assist in the management of blackgrass. This technique incorporates what I have learned about the subject. I call it the **BEN** theory.

This is far more logical than the current approach in the UK of allowing self-selection by this "non-native" plant (blackgrass) that is able to germinate all year round, under any cultivation methods and in any crop!

> **The BEN system is the first opportunity in a decade where the control of blackgrass could be given back to the farmer, rather than the farmer chasing the blackgrass problem.**

BEN is a new system that could aid the management of blackgrass by using knowledge of selection and implementing it into the rotation :

Blocking rotation – by putting crops and cultivations into blocks

Enhancing selection for blackgrass over periods of 5 years

Neutralising the blackgrass by changing things around

Details of the BEN rotation are given overleaf in Table 4.

The first 5 years are planted in a simple winter wheat and winter oat **B**lock rotation. Both are planted at similar timings (late October) and established with a direct drill. **E**nhanced selection of the blackgrass will be 2-fold. Firstly the blackgrass will self-select to grow in late autumn and early winter, and secondly it will also self-select for non-disturbed soils.

The **N**eutralisation comes about in year 6 when the field is accurately winter ploughed so burying all seed, and then direct drilled for another **B**lock of 5 years with a spring cropping rotation. **E**nhancement of the blackgrass will shift to spring germinating and, again, in undisturbed soil will self-select for non disturbed plants.

Neutralisation comes again in year 11 when cropping is **B**locked for another 5 years. This time selection for early germinating blackgrass will be **E**nhanced by planting winter oilseed rape and September-planted winter barley. Surface cultivation and stubble rakes will this time be used for eradicating herbicide-resistant blackgrass and also selecting away from the non-disturbed blackgrass to those that thrive in disturbed soils.

The years 11-15 also allow for the use of inter row cultivations such as the Garford Robocrop hoe guided by a camera, giving more disturbance in the seedbed to yet again allow for different selection pressures. By using this method, a farmer is able to stay one step ahead in an applied and planned approach that uses Darwin's theory to help maximise 'peaks' in an emerging graph and then neutralising those peaks and making the greatest impact. Five years of spring cropping might seem a bitter pill to swallow, but many are already looking at double spring cropping and therefore in a standard rotation there might already be as many as 4 such crops over a 12 year period. The **BEN** system only suggests using 5 in a 15-year rotation (Table 4 below).

BEN System		
Year	**Crop**	**Cultivation**
1	Winter Wheat	Direct drill
2	Winter Oats	Direct drill
3	Winter Wheat	Direct drill
4	Winter Oats	Direct drill
5	Winter Wheat	Direct drill
6	Spring Barley	Plough
7	Spring Oats	Direct drill
8	Spring Wheat	Direct drill
9	Spring Barley	Direct drill
10	Spring Oats	Direct drill
11	Winter Oilseed rape	Surface/ inter row cultivate
12	Winter Barley	Surface/ inter row cultivate
13	Winter Oilseed rape	Surface/ inter row cultivate
14	Winter Barley	Surface/ inter row cultivate
15	Winter Oilseed rape	Surface/ inter row cultivate

Figure 54: Table 4: New crop and cultivation rotation following the BEN system.

Possibly the greatest impact of this system will the need for machinery: surface cultivator, stubble rake, a plough to use once every 15 years (possibly use a contractor but, paid by the hectare, contractors are unlikely to drive narrow furrows at a 6kph forward speed and keep dismounting to check for seed burial) and the possibility of two drills. (One, a disc drill to operate in dry conditions in early autumn and some spring crops, plus a tine drill for the late autumn/early winter slot as well as some early spring drillings.)

On a visit to Shimpling Park farm (organic), Suffolk UK, John Pawsey the farm owner explained the System Cameleon drill (Figure 54 below). It is not only a drill but can be very simply converted into an inter row hoe, so covering two machines in one; plus its ability to be a companion crop drill and various other combinations.

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Figure 55: System Cameleon drill. Once drilling the crops is finished, the machine can soon be changed into an inter row hoe. (Shimpling Park, Suffolk, UK)

Chapter 16: Conclusions

1. Because of the quantity of seeds produced each year blackgrass possesses the ability to cope with changes in farming technique: delayed drilling, no disturbance drilling, spring cropping and herbicides. It could ultimately self-select to germinate for 10 months of the year.

2. No-till systems and conservation agriculture slash the options for controlling blackgrass

3. Blackgrass only colonises freshly cultivated ground and is not considered a competitive weed in relation to finding it in pasture, hedgerows or permanent crops.

4. Blackgrass can cope with wet conditions far better than cereals and rape can, due to the formation of aerenchyma. Drainage is essential to give arable crops the best chance against blackgrass.

5. There are many disadvantages to cover cropping as an aid for the control of blackgrass.

6. Mechanical weeding is essential as a blackgrass control tool and to remove herbicide resistant survivors.

7. Soil classification/description in the UK is far too subjective, and needs to be more quantifiable which can be achieved easily.

8. UK arable farming is at a disadvantage compared to many overseas countries because of the sheer scale of their operations

9. The **BEN** system provides a sound alternative answer to the blackgrass problem.

Chapter 17: Recommendations

The report closes with the following recommendations:

1. Understand artificial/natural selection in order to provide a much clearer understanding of how to manage blackgrass issues.

2. Soil type needs expressing in terms of clay percentage, ideally with sand and silt analysed as well, in order to have a clear understanding of what soil character is being considered.

3. Cultivations are vital. Mechanical removal of a weed which has herbicide resistance prevents it from producing seed.

4. Glyphosate abuse is a real problem in conservation agriculture. Glyphosate needs protecting as a product.

5. Using GMO seeds for glyphosate resistance would lead to more glyphosate being used and the potential for glyphosate resistance increasing further.

6. Biological controls could prove to be an excellent addition to the integrated multi-pronged attack on blackgrass.

Adoption of the BEN system would put farmers back in control of the blackgrass situation in the knowledge that they are selecting to eventually neutralise.

Chapter 18: After my study tour

My study tour has led me to a fundamental change of thinking when it comes to blackgrass management, which can be rolled out across any part of the agricultural industry in terms of weeds, diseases and pest management. Selection is highly possible in any population, but mutations are totally dependent on the population size. At least one trillion blackgrass seeds are produced and returned to the seed bank each year and therefore the amount of mutations allow for rapid selection if and when required.

I believe that communication of the conclusions and recommendations of this report needs to be thoroughly planned and organised in such a way that it can be rolled out and explained to individuals and groups in a way to avoid confusion.

My study should be a catalyst for changing soil texture classifications immediately. Classification using the words ‘heavy’ and ‘light’ must stop as they have no meaning to anyone other than the person describing the particular soil. I intend to discuss this with relevant soil analysing companies as well as agronomists that offer a soil sampling service.

If it is to work, the adoption of **BEN** needs to be holistically embraced otherwise the peaks of blackgrass selection will not rise and therefore not be neutralised when the system is designed to do so.

Ploughing will be a challenge. Many growers haven’t ploughed for many years and some have long since sold their ploughs assuming they would never be needed again. Reports from various research sources suggest ploughing does a very good job in the battle against blackgrass. However in practice, most results are disappointing. This in part is due to the difference between good timely ploughing and ‘browning’ the soil, which can produce totally different results and the knowledge of yesteryear ploughmen on how to set a plough up correctly is another knowledge source that is being lost from the industry. Interestingly the most informative information about setting ploughs correctly came from visiting a local ploughing match, where ploughmen were happy to chat about the techniques that improve ploughing for weed control. After all, weed control is 20 points of the ploughing match score when judged. Ploughing matches have a role to teach these techniques once more.

I intend to travel around universities and education centres that teach ploughing and speak with lecturers and students about the importance of correct ploughing looking at: low forward speed, furrow widths, balance, tyre size, tyre pressure, skimmer setup, discs, depth, beam angle, cross shaft length, under beam clearance, inter body clearance, mouldboard height, top link, front furrow, and plough leg angle. Farmers also need educating. Winter ploughing is not something that is done in the wet after everything else is done, ploughing needs to be done in the autumn. This creates a wonderful soil in which to direct drill the spring crop, having allowed the winter weather to prepare the seedbed.

The biological research will continue with Dr Anne Kennedy and the team at Washington State University working on blackgrass seed and bacterial control. When a bacteria is identified, the field scale trials can begin.

Ben Taylor-Davies
June 2017

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Glossary – see overleaf

Glossary

Aerenchyma	(in simple terms) an open pathway which allows oxygen movement from above the soil or water level, down to the roots
Allelopathy	The process whereby plants are able to communicate with each other through root exudates
Hypoxic	Deprived of adequate oxygen supply at the tissue level
Martian environment	An environment which fulfils every requirement of the Martian plant's life cycle, allowing it to become dominant in its new environment
Martian plant or weed	One that originated in another country or continent
Post emergence spraying	Spraying with herbicide after the crop has germinated. This cannot be with glyphosate except in those countries where the use of GMO seeds bred to be resistant to glyphosate is permitted. However there are a few other non-glyphosate herbicides available for post emergence spraying in the UK.
Pre emergence spraying	Plant the cereal first then within 1-2 days spray the weeks with glyphosate. A fine seedbed is essential for this technique to work
Stale (or false) seedbed	A seedbed is created in a field and blackgrass seed will germinate in it. The blackgrass can then be sprayed with glyphosate or killed off with cultivations. The latter will inevitably disturb the soil causing more blackgrass to germinate.
Suberin	An apoplastic barrier at the outer cell layers of the roots that reduces radial oxygen loss from the aerenchyma and prevents toxic compounds from entering the root.