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FORESIGHT PROJECT ON GLOBAL FOOD AND FARMING FUTURES

Global advances in weed management

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SUMMARY

Weeds have been controlled so successfully by herbicides, subsequently supplemented by transgenic herbicide-resistant crops, that past intractable problems have been ignored and new ones are evolving. However, industry-led discovery of new herbicide targets is now lacking and weed science as a discipline is contracting globally. This paper describes novel technologies for dealing with major problems, including: better understanding of weed biology coupled with genomics; novel herbicide-resistant crops as well as engineered weed-competing crops; multi-target herbicides; and enhanced biocontrol agents. Together, these approaches may comprise the components of future integrated packages to slow down the evolution of new weed problems.

INTRODUCTION

The double-edged sword; excellent weed management; no incentive to deal with the future

Weeds are a major constraint to crop production and their control is the principal consumer of manpower and variable costs. Deep ploughing and other mechanical and manual cultivation techniques, previously the main methods of weed control, are now heavily supplanted by chemical control such that more than half the pesticides used worldwide are for weed control. Chemical weed control, currently coupled with transgenic herbicide-resistant crops, has been the most rapidly adopted new practice in agriculture (James 2010), resulting in considerably lower costs and reduced environmental impact (Brookes & Barfoot 2010). Spraying herbicides reduces fossil fuel needs for cultivation, especially in minimum tillage. This environmentally benign technology of minimum tillage and deployment of herbicide-resistant crops has yet to be adopted in Europe. Chemical weed control has become so successful that, for the last three decades, fewer weed scientists have been trained; industry severely curtailed the quest for new herbicide targets of action due to the success of herbicides and herbicide-resistant crops. Regulatory authorities are rapidly deregistering older herbicides, often for unscientific reasons, thus limiting the chemical diversity available to farmers and increasing reliance on a more restricted range of chemicals acting on fewer target sites. This situation facilitates the evolution of herbicide resistance and changes in the weed spectra, as naturally resistant weeds begin to dominate. It is ominous that, when there are fewer active ingredients and fewer weed scientists, emerging problems are increasingly threatening crop production worldwide.

A small subgroup of weed scientists has recently entered the genomic era, publishing a book stating reasons why knowing more about the genomics of many different weeds can assist in attaining better weed management (Stewart 2009). Weed biology was an orphan, downplayed by chemical control specialists as being unnecessary because of the success achieved by the discovery and use of herbicides. With the advent of the evolution of resistance, the reasons for the ancient admonition 'know thine enemy' have become apparent and useful in designing better control strategies, many involving molecular techniques (Gressel 2002). Weed genomics may further assist in this reconnaissance into enemy territory and has already provided insights into how a previously rare wild species, *Amaranthus rudus*, evolved rapidly into a major weed (Trucco *et al*. 2009).

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CURRENTLY INTRACTABLE MAJOR WEED PROBLEMS

A few intractable global weed problems are discussed below. They show how dangerous the complacency of industry and academia, linked with the regressions in science-based regulatory regimes, has become to the world food security.

Emerging problems of grass weeds related to graminaceous crops

Most of the calories consumed by humans and their livestock come from graminaceous crops: wheat, rice, maize and sorghum. Each of these (except for maize) is threatened by uncontrollable interbreeding weeds, often feral forms of the crop (Gressel 2005). Graminicides (grass-killing herbicides) that selectively kill these weeds in these related crops have not been developed, but the technology of employing genetically engineered maize with resistance to broad-spectrum herbicides (glyphosate and glufosinate) to control grass weeds has been used extensively with success. However, this approach has not yet been deployed in other graminaceous crops, and neither should it be, unless measures are taken to prevent transgenes from establishing in populations of the interbreeding weeds.

Rice

Rice is threatened by two major problems (Gressel & Valverde 2009*a*, *b*). Two different *Echinochloa* species have evolved resistance to all the known rice herbicides. More serious is a form of feral rice (weedy, feral or red rice) that crosses easily with cultivated rice. This weed had been controlled by hand transplanting the crop to give it a competitive advantage over the weed by virtue of a month's advance in its development. Industrialization has decreased the manpower (actually mainly woman power) willing to transplant rice, and there is at present no method for dealing with weedy rice.

Wheat

Almost all herbicides that are selective in wheat behave in this way because they are detoxified by cytochrome P_{450} monooxygenases (Gressel 1988). Weeds of wheat have been evolving resistance to these herbicides by up-regulating these enzymes (species of *Lolium* throughout the world, *Alopecurus* in Europe, *Phalaris* in India and elsewhere) or by selection of mutations of the target binding site of the herbicide (Heap 2010). *Aegilops* species that can interbreed with wheat are naturally resistant to the same herbicides as wheat and are becoming increasingly important as weeds.

*Sorghum (*Sorghum bicolor*) and maize*

Shattercane (also *S. bicolor*), a feral weedy form of sorghum, has become an uncontrollable weed in sorghum and maize wherever these related grains are grown.

Perennial weeds in crop production

Perennial sedges (*Cyperus* spp.) and Johnsongrass (*Sorghum halepense*) have long been in the top 10 worst weeds of the world (Holm *et al*. 1977). They have underground storage organs and while many herbicides will desiccate the above-ground portions, they readily re-emerge from underground buds. These weeds were controlled to some degree by mechanical cultivation and by a few systemic herbicides such as glyphosate. However, they emerged as a greater problem in minimum tillage agriculture, but could be controlled readily in transgenic glyphosate herbicide-resistant crops. The evolution and rapid dispersal of glyphosate-resistant *S. halepense*, spread both by seed and rhizomes, first in Argentina and more recently in the USA (Heap 2010), is ominous.

The last group of systemic herbicides developed by industry (three decades ago), the inhibitors of acetolactate synthase, is highly prone to the evolution of herbicide resistance by mutation of the herbicide target binding site. There are a few herbicide groups that remain available for use in the European Union, too few to have much value in resistance-delaying rotational strategies.

Root parasitic weeds

Parasitic *Orobanche* species around the Mediterranean basin into Eastern Europe and Asia, and *Striga* species in sub-Saharan Africa, threaten all major vegetable and grain crops, respectively, in these regions (Gressel & Valverde 2009*b*). The problems are becoming worse, especially in subsistence agriculture in Africa, where cultivation of the host grain crops is intensifying because of food insecurity. However, the result is a decrease in food security, because monoculture has intensified, facilitating parasitic weed dispersal and establishment. There are no really usable widespread technologies for their control except for the deployment of transgenic or mutant herbicide-resistant crops.

Summary: why have weed problems worsened?

Chemical weed control, now coupled with herbicide-resistant crops, has become so successful that there has been complacency and a belief that there would be fewer problems and less need for weed science. The major under-investment in herbicide target discovery (and thereby herbicide chemo-diversity) coupled with

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the advent of unscientific regulatory systems are major negative developments with dire implications for the future. The movement away from manual labour in a leading crop (rice) in the developing world and decrease in fossil fuel-intensive mechanical cultivation in the developed world has exacerbated weed problems and accentuates the need for new chemical methods. Problems with parasitic weed are spreading, and simple solutions are lacking. The over-dependence on a single herbicide/transgenic herbicide resistance in many crops and its consequences generates concomitant needs for new and better resistances, coupled with other weed control strategies in more comprehensive, integrated management packages. The present regulatory environment fosters the development of chemical and/or biotech solutions only for major crops, leaving minor (often valuable) crops in a weedy vacuum.

TECHNOLOGIES THAT ARE EMERGING OR SHOULD EMERGE

Complacency has become entwined with market considerations. With the current success of present weed control products and technologies, there is little economic incentive to deal with emerging weed problems. This is true in the developed world as well as poorer countries. For example, in sub-Saharan Africa where parasitic weeds are rampant, public sector interest in weeds has decreased after the Rockefeller Foundation ceased investing in agricultural R&D. The agro-chemical and agribiotech industries see little market potential in this area, a mistake not made by the telecommunication and appliance industries that have developed specific products for these markets (Gressel 2004*a*).

Below are some ways in which novel technologies and new paradigms could enhance weed management. It is imperative that novel methods of weed management exclude mechanical cultivation as far as possible since it currently represents a major use of fossil fuel and source of greenhouse gas emissions from soil by virtue of the level of disturbance. Ironically, organic agriculture depends almost solely on mechanical weed control.

New herbicide mode of action discovery

Most major agrochemical companies adopted a genomics approach to the search for new herbicide targets by using *Arabidopsis thaliana*. This dicotyledonous species is not a competitive weed and therefore is not a biological model for grass weeds or perennial weeds. The chemicals with herbicidal activity that might have been found would almost inevitably be single-target inhibitors, because of the screening for molecules that inhibit a single essential gene product (Gressel 2008). Such new herbicides, if they had been found, would be prone to the rapid evolution of resistance. The failure of this approach to discovery was owing to companies' lack of lead compounds that might inhibit the potential targets elucidated by genomics.

There are hundreds of well-authenticated lead phytotoxic compounds known that do not inhibit any known target site and are also without known evolution of resistance. However, these compounds have been mostly ignored by industry (Gressel 2002). They are the phytotoxic chemically characterized allelochemicals produced by plants and microbes (Dayan *et al*. 2009). One reason that these natural compounds are not prone to the evolution of resistance is probably due to their being multi-site inhibitors. It would seem appropriate for industry to pay more attention to seeking analogues of these complex molecules that could perhaps then be modified to obtain greater crop selectivity. The chemical/molecular tools are now far more sophisticated than in the past; the moiety that binds and inhibits can be ascertained and coupled with chemical groups that crops can naturally metabolize, or that crops can be engineered to metabolize (see further). Hopefully, some of these new herbicides will be naturally systemic, or innovative chemists will learn how to modify them to be systemic so that perennial and root parasitic weeds can be controlled.

As discussed above, the incentive to discover new herbicide targets has been stifled by the availability of inexpensive glyphosate, together with glyphosate-resistant crops taking such a large market share. The rapidly emerging glyphosate resistance in weeds should engender a desire to retain this herbicide as long as possible, which could justify regulations that assist in this goal, while providing incentives to develop new herbicides. Glyphosate resistance could be delayed by requiring glyphosate to be marketed exclusively as a premix with at least one other herbicide.

Engineered crops resistant to contemporary herbicides

Most transgenic crops planted to date are transgenic herbicide (mainly glyphosate)-resistant crops, leading to the problems described above. These problems are not an argument against the developing and deployment of herbicide-resistant crops. On the contrary, the economic success of these crops, together with their beneficial environmental impact, vindicates the approach but warns against overuse of a single herbicide resistance. Some possible ways in which this diversity might be provided are discussed below. There have been efforts to obtain herbicide-resistant crops by mutagenesis or by using the specific gene conversion processes of chimeroplasty, neither of which are defined as transgenic. If the mutations are single base changes, as has been the case with the

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imidazolinone-resistant crops, then weeds can continue evolving resistance, or the mutant gene can rapidly transfer by hybridization to taxonomically related weeds, ending the utility, as with rice (Shivrain *et al*. 2009) and wheat (Gandhi *et al*. 2006). There are transgenic ways to prevent such gene flow (see further).

Engineering resistance to less resistance-prone herbicides

There have been very few cases of resistance evolving in weeds to two groups of widely used herbicides: the inhibitors of very long-chain fatty acid biosynthesis (chloroacetamides and similarly acting compounds) and protoporphyrinogen oxidase inhibiting compounds (diphenylethers and other chemical groups affecting this target) (Gressel 2002; Heap 2010). While neither herbicide group is systemic, which would allow control of root parasitic and perennial weeds, they do have many uses, and the long-chain fatty acid inhibitors are excellent grass killers. There are crop species that metabolize members of each group, and so there must be genes that could be isolated and transferred to other crops. Fascinatingly, most researchers have eschewed using plant genes to obtain metabolic resistance even though such genes might more easily satisfy regulatory regimes, since it is known how the naturally resistant crops metabolize these herbicides and they should therefore be regarded as safe.

Engineered herbicide resistance to newly developed herbicides

The rational design of new herbicides based on multisite natural allelochemicals (see above) will allow engineering of metabolic resistance to the same herbicides in order to effect crop selectivity. Technologies are now available to isolate genes encoding herbicide metabolism both from culturable and unculturable microorganisms. When such genes are too inefficient to perform the metabolic task with judicious speed (high K_m, low V_{max}, where high K_m = a high concentration of substrate that leads to half-maximal velocity (V_{max}); V_{max} = the limiting reaction velocity as substrate concentrations become very large), gene shuffling can rapidly evolve poor genes to better ones (Castle *et al*. 2004).

Thus, novel herbicide discovery technology and novel biotech could combine to alleviate many problems. Cultivating more weed-competitive crops such as barley instead of poor-quality wheat requires removing wheat subsidies, and would enhance the possibilities of designing better weed control strategies.

Resistance management in herbicide-resistant crops

Engineered resistance to less resistance-prone herbicides would be helpful, but resistance can evolve by more than one mechanism, some totally unpredictable. Thus, it is unwise to believe that resistance cannot evolve, as had been the (manufacturer's) predictions for glyphosate (Bradshaw *et al*. 1997).

Resistance management can be as simple as hand rouging uncontrolled individuals before they set seed, to complicated rotations or sequential applications. For example, at present the only herbicide mechanism to control parasitic *Striga* on maize is to use (mutant) imidazolinone-resistant maize, with the seed coated with herbicide (Kanampiu *et al*. 2009). *Striga* could evolve resistance, especially in long-season maize. Other weeds are hand weeded in this crop, despite women having better things to do. If the mutant imidazolinone resistance were stacked with transgenic glyphosate resistance, a single mid-season glyphosate treatment would control any emerging imidazolinone-resistant as well as susceptible *Striga* (systemically through the maize) and other weeds, and during the next season the seed treatment would control any glyphosate-resistant *Striga* that evolved. A more complex scenario of stacking is described in the following section.

Failsafes from gene flow to related weeds

As discussed earlier, there are feral weedy forms of many important crops including rice, sorghum, sunflower, oilseed rape, oats and beets, as well as weeds that are sufficiently related to wheat, sorghum and oilseed rape to cross with them. Selective herbicides do not control these related weeds in these crops, but they can be controlled by transgenically rendering the crop resistant to the herbicide. Alas, the resistance genes can introgress from crop to related weeds.

Strategies proposed for gene containment are all 'leaky', e.g. maternal inheritance of chloroplast traits has not prevented gene flow by pollen. Mitigation strategies have been proposed to prevent the establishment of weed–crop hybrids and their back-crosses with weeds (Gressel 1999) and have been demonstrated to work under field conditions (Rose *et al*. 2009). This requires tandem coupling the gene of choice (e.g. herbicide resistance) with a gene that is positive or neutral for the crop but devastating for weeds (e.g. no seed shattering, dwarfism, no secondary dormancy and no premature bolting). Genes in tandem cannot segregate and remain linked, conferring continuous unfitness on the hybrids that are unable to compete. This may not be sufficient for monoculture paddy rice. It was proposed to generate different transgenic herbicide-resistant varieties for rice, each with mitigator genes that confer hypersensitivity to the next herbicide in the rotation, facilitating

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selective culling of hybrids (Gressel & Valverde 2009*a*). This, coupled with an unfitness trait such as non-shattering of seeds, should keep the hybrids from establishing while controlling the weedy rice forms along with other weeds.

There have been more scientific papers decrying the perils of gene flow than those dealing with it, and it is unfortunate that the biotech seed industry has not so far been inserting failsafe mechanisms into transgenic crops having interbreeding weeds. Industry opens itself to the criticism of being cavalier in their care of weed management issues, and is open to the future loss of a good technology, as was the case of the mutant-derived imidazolinone-resistant rice, which lasted but 2 years in some locales (Gressel & Valverde 2009*a*). Short-term economic gain seems to overcome long-term economic corporate interests as well as agricultural needs.

ENGINEERING WEED-RESISTANT CROPS

Why apply a chemical herbicide if the crop can control the weed? Plants do make allelochemicals that are toxic to other species; why not move them transgenically to where they are needed? Such suggestions should be viewed carefully on a case-by-case basis. Some allelochemicals are toxic to mammals and if proposed as sprays would never pass regulatory authorities. Crop ecologists continually reiterate that plants can either grow or defend (Herms & Mattson 1992), with defence at the expense of growth. When it comes to yield value, the allelochemicals, as made by the crop, are usually more expensive to synthesize than pesticides (with some exceptions), when the allelochemicals are stable proteins. Thus, Bt toxin produced transgenically by a crop is much cheaper than synthetic insecticides. There are no reports yet where crops have been engineered to control weeds by secreting allelochemicals. Still, low-molecular-weight agrochemicals are not the only way to control weeds by genetic engineering.

Engineering parasitic weed control via interference RNA molecules

Small interference RNA molecules (RNA_i) are known to go from the crop to attacking pests. Plant RNA_i, targeting a nematode-specific gene, has been shown to kill nematodes attacking the plant (Huang *et al*. 2006). It was proposed to use a similar strategy with parasitic weeds, as RNA traverses short distances into parasitic weeds. A first attempt targeted gene sequences in primary metabolic pathways whose inhibition should kill a plant. RNA_i was constructed for non-consensus sequences of those genes, so as not to injure the crop, but the parasite was not controlled (De Framond *et al*. 2007). As *Orobanche* stores and uses mannitol and crops do not, a more recent attempt targeted a gene encoding mannitol metabolism and a modicum of control was achieved (Aly *et al*. 2009), suggesting that this is the right direction. The RNAi approach has applicability only with parasitic weeds that attach to crops.

Engineering weed-stifling crops

There are many levels where a crop might be induced to better compete with weeds. No single level could work like a herbicide, but stacking many such genes might provide a competitive edge that would either preclude the need for herbicides, or allow herbicides to be used as a *coup de grace*. As noted above, the mechanisms must not reduce yields appreciably. For example, a more extensive root system that assists in competing for water and minerals might be too expensive. The green revolution demonstrated that taller weeds shading growth halved yields, which justified herbicides for control of weeds in dwarf crops.

Traits such as better fertilizer utilization are becoming valuable and if the crop roots were engineered to quickly and efficiently take up minerals, weeds would be stunted. Over-fertilization led to luxurious weeds. Genes are known and available for phosphate solubilization and uptake, iron uptake, etc., and might be used for this purpose.

A more controversial strategy would be to engineer a single variety of a crop to have many different leaf morphotypes and leaf angles, leaving other traits as isogenic (Gressel 2002). This crop would quickly shade the soil surface, keeping light from weeds. Crop yields would increase due to more field area being used for a longer duration by crop photosynthesis. The problem is not in engineering; genes that would fulfil the function are rapidly becoming known. The problem is with varietal regulatory authorities who require morphological uniformity. Such thinking must be overcome.

DOMESTICATE HIGHLY PRODUCTIVE WEEDY SPECIES AS CROPS

The major crops derived from rapidly growing weedy species were slowly domesticated. Most domestication traits, such as non-shattering of seeds and uniformity of germination (no secondary dormancy), are hard-to-select recessive traits. Some recently domesticated crops, such as oilseed rape, still have seed shatter problems requiring harvest at highly specific times. Some incompletely domesticated weeds, e.g. seed amaranth (*Amaranthus* spp.), quinoa (*Chenopodium quinoa*), fonio (*Digitaria exilis* syn *Paspalum exile, Syntherisma exilis*), tef (*Eragrostis tef*), birdseed millet (various species) and many others, can be highly competitive with weeds (Gressel 2008). They can be

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further domesticated more rapidly using transgenics. Transgenes are inherited as dominant traits. Such ex-weeds-cum-domesticated crops can be used for suppressing weeds and rotated with other crops, requiring fewer chemicals.

BIOCONTROL OF WEEDS

The use of weed pathogenic micro-organisms or insects has been highly successful in some cases where a weed was introduced to a virgin area without its natural enemies. This 'classical biocontrol' entailed finding these enemies. The most pernicious weeds have become continental or global, adapting themselves so well that they have no real natural enemies. The best that researchers could do in such cases was to find pathogens that diseased but did not normally kill the weed, and apply them at excessive inoculum levels – typically 100 spores/mm^2 of weed leaf surface (inundative biocontrol). Even then, at times only a hypersensitive response was achieved. Few potential biocontrol agents reached market and none were major commercial successes. This is unfortunate, because the control of a single problem weed often allows the use of lower levels of herbicide to control other species. Biocontrol strategies with native weed-specific pathogens are doomed from an evolutionary perspective. If a species specific pathogen (or insect) provided the level of control demanded by the farmer, both the pathogen and weed would become extinct. Thus, it has been proposed to increase the virulence of pathogens by adding transgenes encoding phytotoxins or other genes enhancing virulence. Hypervirulent pathogens can be propagated in culture, and so they will not become extinct. Although this approach has been successful in the lab (Amsellem *et al*. 2002), it is questionable in today's regulatory environment whether one could release such organisms in the field, even though transgenic failsafe mechanisms have been proposed that would keep them from moving off the target (using asporgenic deletion mutation) and from successfully conjugating with pathogens (Gressel 2004*b*).

MIXING STRATEGIES – AN IMPERATIVE FOR SUCCESSFUL SUSTAINABLE MANAGEMENT

Heavy mechanical control of weeds is hopefully an energy-wasting procedure of the past, except as a last resort. Hopefully the paradigm of KISS (keep it simple, stupid) is also a concept of the past, and with further amalgamation and automation in agriculture and with remote monitoring and global positioning system (GPS), agriculture will adopt a new KISS = keep it sophisticated smarty. Monoherbicide and monocrop culture was doomed to last not more than a decade or so. Weed resistance and shifting weed spectra preclude monoherbicide culture. Hopefully, the trend towards decreasing options for weed control will stop before too many errors are made. There are too few inputs remaining for weed control, and so the farmer must be sophisticated to decide on how to mix or sequentially use them to maximize weed control. Decisions must be made based on knowledge of the biology and phenology of the weeds in the field to design rotations, where each crop naturally suppresses weeds for the following crop. Decisions on herbicide use and rate must be based on the weeds expected to be in the field, or post-emergence based on the weeds in the field to be controlled in the particular crop, and those that must be suppressed for the next. Dose decisions are not easy: how much weed is to be killed? How much weakened? Knowing that, with some herbicides, high dose rates are selected for target site resistance and low doses for multi-factorial (polygenic, gene amplification and multiple allelic) resistance, which in some cases may confer cross resistances to herbicides of different chemistries and modes of action, decisions become harder. The newly sophisticated farmer now understand that the more varied the control mechanisms used in a rotation, the longer the duration each will have on the desired effect. A confused enemy weed is one that is easier to deal with. As aerial field monitoring becomes more sophisticated, the farmer will be alerted to weed patches in real time that need special treatment and further monitoring. Compatible software from aerial monitoring will quickly tell the farmer if pre-programmed GPS robotic treatment of the patches was effective. Presently available remote sensing is not sophisticated enough to differentiate between weed species, yet the farmer must make decisions based on weeds.

To be able to achieve all this, the farmers need new crops to introduce into rotation, lessening reliance on major grain crops and to be better able to confuse the weeds. In the next few decades, seaside deserts may be covered with marine algae farms producing high-quality animal feed, with better fertilizer utilization than conventional crops, sequestering industrial carbon dioxide and not using fresh water, while attaining much higher yields than conventional agriculture (transparency: the author is associated with a company developing algae for this purpose). This will free agricultural land for more varied speciality crops, and more crops in rotation will allow easier rotation design for weed control.

If farmers have an arsenal of new and older herbicides, many different conventional and transgenically herbicide-resistant crops, crops engineered to suppress weeds and enhanced biocontrol agents for specific weeds, then the wise and sophisticated farmer can manage weeds at the lowest cost over the longest time period, without major new problems. Will we have a research structure providing these tools and a regulatory regime encouraging the development

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of safe new ways of weed control? The current trends are in the wrong direction, despite signs that it is necessary to act together for ensuring food and fuel security.

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