AN ECOLOGICAL PERSPECTIVE ON THE USE OF HERBICIDE TOLERANT CROPS IN INTEGRATED WEED MANAGEMENT

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Summary Transgenic crops are the subject of considerable commercial interest in the fight against weeds. Large investments have been made into herbicide tolerant crops and good selectivity in previously susceptible species has been reported or can in some cases be engineered. A number of herbicide tolerant plant projects currently under way in Australia, involving cotton, lupins, canola and pasture legumes, together with hypothetical cases, are examined to evaluate the many claims that these initiatives will significantly improve the efficiency of weed management. The future weed problems and ecological criteria for evaluating the role and impact of herbicide tolerant crops, from an integrated weed management perspective, are also considered.

We conclude that many of the claims for improved efficiency in weed management are extravagant, particularly in broadacre farming systems with diverse weed floras. In some cases, the use of herbicide tolerant crops could result in a loss of herbicide options, more expensive fallow weed management, a reversion to tillage and a greater dependance on herbicides, all of which are undesirable outcomes. Their use could also hasten the selection for herbicide resistance in some weeds, and worse, could leak resistance genes to close weed relatives. It is unlikely that single trait herbicide tolerant crops would have wholesale application in broadacre dryland no-tillage farming systems. No one herbicide can provide adequate spectral control, and any partially selective advantage afforded by a herbicide tolerant crop will be short lived because of the dynamics of diverse weed floras. At best they may be useful as strategic tools for short term management of specific weed problems. Because each case involves a complex array of advantages and disadvantages, we advocate that every proposed herbicide tolerant crop initiative be subjected to careful benefit/cost analyses.

We advocate the adoption of any herbicide resistant crop be promoted responsibly in the context of an integrated weed management program, not as a panacea. This is essential to maintain the credibility and impetus of conservation farming and integrated weed management adoption programs. We also recommend that either regulatory guidelines be implemented, or that industry develop a voluntary code of best management practices, to provide accreditation of herbicide tolerant crops so that markets and the environment are protected.

INTRODUCTION

Transgenic crops are being developed and promoted for their potential to improve product quality, and resistance to herbicides, pests and diseases. Herbicide tolerant crops comprise approximately one third of all transgenic initiatives; the major crops chosen being lucerne, maize, cotton, flax, canola, potato, soybean, sugarbeet, tobacco and tomato. Herbicide tolerance has been incorporated into wheat and sorghum cultivars but these are not currently under commercial development. Field releases of transgenic plants with tolerance to glyphosate, glufosinate, sulfonylureas, and bromoxynil have been made.

A number of potential advantages of herbicide tolerant crops have been advocated: better, easier, and cheaper weed control; overall reduction in herbicide use; reduced preventative use of herbicides; increased use of minimum tillage; displacement of residual herbicides; control of weeds closely related to the crop; broader spectrum weed control; and options for controlling herbicide resistant weeds. On the other hand transgenic technology has raised public concerns because it involves the use of pesticides as well as genetic engineering, resistance genes may escape to weedy relatives, and undesirable shifts in the weed flora may be induced through the selection of tolerant or resistant species. These claims are examined in this paper by considering initiatives currently under way in Australia involving cotton, lupins, canola and pasture legumes, together with hypothetical cases of wheat, sorghum and chickpeas in the context of the north-eastern grains region of Australia. Our deliberations are focused primarily on the ecological impacts of herbicide tolerant crops on integrated weed management and farming systems with the aim of developing criteria that can be used to better assess herbicide tolerant crop applications that are submitted for registration.

DEVELOPMENT OF HERBICIDE TOLERANT CROPS IN AUSTRALIA

In Australia, there is considerable current interest and activity in the development of herbicide tolerant varieties of cotton, lupins, canola and pasture legumes.

Cotton Herbicide resistance genes have been identified in cotton for 2,4-D, bromoxynil, glyphosate and sulfonylureas and these have the potential to reduce the amount of broad spectrum residual herbicide used (Charles *et al.* 1995). A glyphosate tolerant cotton would greatly enhance the ability to manage one of the industries most recalcitrant weeds, nutgrass (*Cyperus* spp.). With cotton being increasingly grown in dryland mixed farming systems, a glyphosate tolerant cotton has the potential to become a serious volunteer weed of fallows. The potential for gene escape from cotton to weeds or other crops is low and it is unlikely the technology will encourage irresponsible herbicide use. To ensure this, research is needed to integrate chemical and cultural management strategies into weed management systems in order to minimize the chance of weeds developing herbicide resistance and to avoid the build-up of herbicide tolerant weeds.

Cotton is a high value, high input crop which is heavily serviced by consultants, so any new agronomic technology is quickly transferred to the industry. There can be little doubt that a glyphosate tolerant cotton variety would be widely adopted by cotton growers provided the transgenic variety does not result in any yield or quality penalty.

Lupins Genes for resistance to glufosinate have been incorporated into commercial lupin varieties in Western Australia (Hamblin and Atkins 1995). This initiative was taken largely in response to the development of resistance in annual ryegrass (*Lolium rigidum* Gaudin) to a wide range of herbicide groups. Besides permitting selective control of ryegrass with glufosinate, its use would reduce the dependence on less desirable residual herbicides such as simazine. As there are no widespread wild relatives of lupins, the risk of herbicide resistance genes escaping is low. Although some of the ecological implications have been considered in this case, the intention to carry out field research to develop an integrated weed management strategy as part of the program has not been foreshadowed.

Canola Transgenic canola lines have been developed with tolerance to glufosinate and glyphosate in Canada (Salisbury *et al.* 1995) and triazine resistant lines are already in use. They offer the opportunity to replace residual and soil-incorporated herbicides and potentially to use less herbicide. However, some of the most troublesome weeds in canola are closely related members of the family Brassicaceae and there is a high risk that transfer of resistance genes can occur (Dale and Irwin 1995).

Pasture legumes Transgenic herbicide tolerant pasture legumes would potentially enable better control of broadleaf weeds in pasture (Dear *et al.* 1995). Current herbicide options are limited because they cause excessive damage to pasture legumes. Herbicide tolerant pasture legumes would enable the development of more sustainable crop-pasture rotations with improved nitrogen fixation and a longer pasture phase. Dear *et al*. (1995) called for an expansion of guidelines to include a program of basic research into the ecology of transformed plants to support field evaluation programs.

POSSIBLE SCENARIOS APPLICABLE TO THE NORTH-EASTERN GRAINS REGION

The summer dominant rainfall grain belt in north-eastern New South Wales and south-eastern Queensland supports a wide range of winter and summer dryland cropping systems, dominated by continuous winter cereal cropping, wheat/sorghum rotations and wheat/legume rotations. Dryland cotton also has become an important crop in the region. Unfortunately, the region is infested by a diverse weed flora with over 100 species occurring in summer fallows alone (Felton *et al.* 1994). It is characterized by highly erodible soils, and unreliable rainfall distribution. Water is the prime growth limiting factor, so crop yield is highly dependent on the conservation of water in the soil during summer and winter fallow periods. Thus management of weeds in the fallow is critical for efficient water storage. Fallow management and seedbed preparation has relied traditionally on repeated tillage practices and the burning of stubble, which has depleted the original high natural fertility. Declining crop yields and grain quality have necessitated a shift to conservation farming, with the retention of stubble and substitution of herbicides for tillage, and rotations with pasture legumes, such as lucerne, or grain legume crops such as chickpeas.

Weeds are a major constraint to sustainable farming systems in the region since they impact on most operations and decisions made throughout a crop/fallow cycle. Farmers are inclined to only treat symptoms as they occur but weed control still accounts for about one third of the variable costs of production and is a significant financial burden to producers. It is noteworthy that the current array of herbicides has done little to alleviate the weed burden because the weed flora is diverse and relentlessly adaptable. Moreover, the increasing reliance on herbicides for weed control could lead to more intractable weed problems and the increased risk of undesirable environmental consequences.

To assess if herbicide tolerant crops have a role in improving weed management in the region we examine three hypothetical, but realistic scenarios: a glyphosate tolerant wheat; glufosinate tolerant sorghum; and triasulfuron tolerant chickpea. The bio-safety, weed management and economic aspects of these cases are discussed more fully by Medd *et al.* (1995).

Glyphosate tolerant wheat The major advantages of a glyphosate tolerant wheat would be to allow cheaper early post-emergence control of grasses, and increase the options for control of seed set through selective spray-topping with glyphosate. To allay the development of herbicide resistance in grasses, the availability of an additional biochemical group for herbicide rotation would be an added advantage. Escape of tolerant genes to weeds would be a minor risk.

Glyphosate is the most cost effective herbicide for fallow management. Because of summer rainfall, volunteer wheat is a major weed of fallows, so additional costs would be incurred to control a glyphosate tolerant wheat. Alternatively, repeated tillage of the fallow would be necessary, and this would be counter-productive to sustainable farming. Glyphosate is a broad spectrum herbicide and is registered for use on about two thirds of the weeds occurring in the region (Medd *et al.* 1995). With such a diverse weed flora, repeated fallow and in-crop use of glyphosate would undoubtedly result in a rapid shift in the botanical composition to tolerant species.

Glufosinate tolerant sorghum Production of sorghum is heavily reliant on atrazine for grass control, but atrazine residues reduce cropping options, and have the potential to contaminate surface and ground water. A glufosinate tolerant sorghum would negate the issues of herbicide carry-over and selective grass control, but at current prices, glufosinate would be double the cost of atrazine and repeated applications would be required to give equivalent control. Being a contact herbicide, glufosinate requires high volumes of water to achieve adequate coverage and this would be a major constraint in the region.

The most serious possible implication of the release of a glufosinate tolerant sorghum would be the control of it as a volunteer weed in subsequent crops and fallows, and the risk of transfer of the resistance gene to weedy relatives such as *Sorghum almum* D. Parodi or *S. halepense* (L.) Pers.

Triasulfuron tolerant chickpea A triasulfuron tolerant chickpea would be a useful initiative for improved, less expensive, post-emergence control of broadleaf weeds, which is currently dependent on pre-emergence herbicides that do not give reliable control.

On the negative side, further use of sulfonylureas would reduce the diversity of herbicides used in the rotation and increase the risk of herbicide resistance developing. Rotations with winter cereals would not be affected by triasulfuron residues but rotations with sorghum would be restricted as the plant back period for sorghum following triasulfuron is 24 months. A significant problem would be encountered in controlling sulfonylurea tolerant chickpea volunteers in subsequent fallows because the preferred chemical option is metsulfuron. Thus a triasulfuron tolerant chickpea could also lead to an increase in the requirement for tillage in the fallow.

EVALUATING HERBICIDE TOLERANT CROPS FOR WEED MANAGEMENT

Commercial considerations There has been an investment of billions of dollars in developing the transgenic technology. There is also a significant ongoing cost associated with germplasm management, seed production, product control and distribution, and legal protection. Commercial developers have to recover these costs and make a profit on their investment. These costs ultimately have to be passed onto the farmers and to agricultural products. To be viable, the transgenic technology has to replace some other production costs, and/or increase productivity in order to improve farm profitability.

Farmers are unlikely to accept the technology if they do not make more money. They also will be reluctant to widely adopt transgenic crops if they were only minor beneficiaries or bearers of most of the risks. That most of the major agrochemical companies have linked to, or acquired, seed companies suggest that they are positioning themselves, rather than farmers, to be the principal beneficiaries of herbicide tolerant crops. However, whilst there is potential for farmers, and possibly consumers to benefit, each case involves a complex array of advantages and disadvantages, and therefore should be subjected to careful benefit/cost analyses, as advocated by Medd *et al.* (1995) and Pratley *et al.* (1995).

Herbicide tolerant crops appear to be commercially best suited to intensive high value enterprises, and perhaps broadacre situations where there are only one or two major weeds which are difficult or expensive to control, e.g. wild radish in canola and resistant ryegrass in lupins, or where current herbicide recommendations are unreliable e.g. broadleaf weed control in pastures and chickpeas. However, these do not represent the majority of weed management problems.

Because of the complexities involved in managing diverse weed floras, it is unlikely that single trait herbicide tolerant crops would have wholesale application in broadacre dryland no-tillage farming systems. No one herbicide currently marketed can provide adequate spectral control, and any partially selective advantage afforded by a herbicide tolerant crop will be short lived because of the dynamics of diverse weed floras (Medd *et al*. 1995). In these situations we envisage markets would be restricted to limited seasonal and strategic uses of herbicide tolerant crops as tools in integrated weed management packages.

Where the weed flora is extensive and weed problems vary with soil types, season and management practices, additional herbicides will be required to provide control of those weeds not adequately controlled by the so called broad spectrum herbicides considered. To be commercially acceptable, herbicide tolerant crops must retain the original cross tolerance characteristics their progenitors had to other herbicides. Alteration of tolerance characteristics by the insertion of alien herbicide tolerance genes would not only incur considerable additional developmental costs through the need for rigorous testing, but could result in the untoward deletion of some current herbicide options from management systems. Such an outcome would be retrogressive. Miflin (1995) also makes the very important point that where herbicide tolerance has been introduced into a crop, the necessity to maintain it through breeding populations and into released varieties places extra burden on the plant breeder and slows the rate of gain in other traits. It is claimed that there is no significant yield penalty with glyphosate tolerant crops such as cotton and soybeans (Wells 1995), but this is not the case for triazine resistant canola (Dekker and Duke 1995).

Some herbicide tolerant crops could also meet with restricted market potential. For example, profitable wheat production is heavily dependent on a wide choice of varieties to cater for different soil types, latitude, disease tolerance and sowing date opportunities. In order to be economically viable, a suite of herbicide tolerant wheat varieties would need to be developed for the technology to capture sufficient market share.

Concerns over the commercial use of genetically manipulated plants *per se* is not likely to be a major issue with farmers, provided there is no associated economic or environmental penalty, but the issue is probably more important to the wider community. Environmental concerns are of increasing relevance and cannot be discounted. Quality assurance now includes environmental accreditation and future market opportunities for products will undoubtedly be related to how these are produced.

Role in integrated weed management There is now widespread agreement that only by integrating desirable tools can there be any hope of managing weed populations more efficiently (Medd 1996). From the examples we have examined, there appears to be limited potential for herbicide tolerant crop varieties to contribute significantly to integrated weed management programs under Australian broadacre farming systems. What stands out is that although there may be a short term gain through better control of certain weeds, e.g. control of close crop relatives in the case of canola, or herbicide resistant ryegrass in lupins, other species will inevitably be selected by the use of these crops and an over dependence on particular herbicides. To check the resultant weed problems, different, possibly even more costly solutions, will be needed. Integrated management takes into account these issues and endeavours to provide both good short term and longer term solutions to our continually changing weed problems. Thus, in the majority of farming systems, herbicide tolerant crops will not provide radical new solutions to, or sustained relief from weeds. It is thus vitally important that any herbicide tolerant crop initiative be promoted, not as a panacea, but as a component of integrated management.

An important claim of the value of herbicide tolerant crops is that broad spectrum herbicides such as glyphosate, which is translocated, can be used as a post-emergence application to improve weed control. However, the efficacy of glyphosate is rate dependent. For example, wild oat is more sensitive than ryegrass, and annuals are generally more sensitive than perennials. Furthermore, there are a number of species that are not reliably controlled at recommended rates of application. Consequently, other herbicides are required, e.g. metsulfuron, 2,4-D or dicamba, either in combination with glyphosate or as an additional treatment, to achieve effective control or to broaden the spectrum of control. Similarly for contact broad spectrum herbicides such as glufosinate, there is no evidence that weed management would be sustainably improved, even though we have eluded to benefits in these cases.

A further claim is that post-emergence application with non residual herbicides is preferable to applying a residual pre-emergence herbicide, because it may increase crop rotation options, as instanced in the lupins case. Post-emergence applications also have the purported advantage of allowing spray decisions to be made on known weed densities. The latter of these claims can not be universally supported, as instanced in the sorghum case, where repeated applications may be necessary to combat protracted recruitment events.

In most of the cases we considered, there would appear to be an increase in the use of herbicides with herbicide tolerant crops, e.g. post-emergence grass control in sorghum and the need for additional herbicides to control crop volunteers such as wheat, cotton or chickpeas. Indeed, current practices are already showing this trend and concerted efforts are underway to promote integrated weed management which aims to establish a sustainable management system by combining all appropriate weed control options. Any new technology, such as herbicide tolerant crops, unless responsibly promoted, could undermine the adoption of integrated weed management principles.

The management of herbicide resistance through the use of herbicide tolerant crops appears to be a flawed concept. The ability for herbicide resistance to develop in major weed species continues to be underestimated by industry, despite the spectacular and disastrous prelude in annual ryegrass. Wild radish (*Raphanus raphanistrum* L.), a weedy member of the family Brassicaceae, has developed resistance to a range of group B and suspected tolerance to group F herbicides in Western Australia (Anon. 1996). Targeting close weedy relatives such as wild radish in canola only with herbicide tolerant crops and particular herbicides can provide a short term fix, but in the long term is likely to result in the loss of herbicide options due to the development of multiple and cross herbicide resistance in the target, as has happened with ryegrass. In the wild radish/canola case, dual forces could be in action – resistant forms would undoubtedly be selected from within this genetically highly variable species and there could well be a transfer of tolerant genes from canola to the weed.

Until there is evidence to the contrary, we must presume that given sufficient pressure, every herbicide has the capacity to select for resistance in most weeds because of their notoriously wide genetic variability. This has occurred with the broad spectrum contact herbicide paraquat (resistant barley grass (*Hordeum glaucum* Steud.)) and, despite industry being adamant that it is unlikely for a sensitive species to develop resistance to glyphosate (Hebblethwaite, Monsanto St. Louis, personal communication), suspected resistance in annual ryegrass to glyphosate has now been revealed (TOPCROP Victoria Newsletter, June 1996).

Impact on farming systems Herbicide tolerant crops need to be examined for the benefits and risks they bring to the farming system. For example, a herbicide tolerant crop species as a volunteer weed in the subsequent fallow may add to the expense of control with herbicides and could even compromise adoption of reduced tillage technology. If a herbicide tolerant crop were used repeatedly, the botanical composition of the weed flora would change rapidly to those that are tolerant of or only suppressed by the prevailing treatment. Furthermore, it is possible that a range of crop species will be developed with resistance to the same herbicide. This could lead to repeated use of the same broad spectrum herbicide and unprecedented pressure on weed populations and potential for development of resistance, and environmental damage.

A concern with herbicide tolerant crops is their propensity to further lock agricultural systems into higher herbicide dependence. Farming methods that conserve the basic soil resource while maintaining yield, have through economic necessity, led to large reductions in the use of tillage to maintain clean fallows and to prepare seedbeds. Herbicides have thus played a significant part through replacing tillage operations prior to seeding and enabling more timely seeding, besides their traditional use for control of weeds after crop emergence. We have highlighted in the wheat, chickpea sorghum and cotton cases that herbicide tolerant crops could compromise chemical fallow management practices through cost increases.

Whilst the reliance on herbicides for fallow management has a sustainable basis, greater dependance on herbicides for in-crop weed management does not. For example, increasing the use pattern of glyphosate by planting transgenic crops, such that glyphosate is used as an in-crop herbicide, will increase the likelihood of glyphosate becoming less effective in fallow management programs. This would be of great concern in the north-eastern grain region. Glyphosate is a most valuable tool in minimum/no-till farming systems and shifting weed problems to glyphosate tolerant, or selecting of resistant species, will substantially reduce the adoption of chemical fallowing. This would seriously prejudice progress in reducing land degradation caused by excessive tillage.

Increased herbicide use also raises the potential for contamination of produce and the environment. In addition, logistical constraints arise, as we have already outlined, through the potential selection of tolerant and resistant weed biotypes, and because of carry-over of herbicide residues that can be phytotoxic to subsequent crops. Although herbicides have brought economic, agronomic and sociological benefits, these risks of undesirable side effects are being increasingly scrutinized. Real and perceived concerns about residues in foodstuffs, soil, surface and ground water and in the atmosphere, effects on non-target organisms and potential herbicide resistance must be addressed, if for no other more paramount reason than to protect both domestic and export markets (McLean and Evans 1995).

Ecological evaluation of transgenic plants The Genetic Manipulation Advisory Committee (GMAC) has established guidelines for work with genetically manipulated plants. GMAC has the responsibility in Australia for surveillance of transgenic plants and has a set of criteria to assess potential risks by the release of the transgenic crop. The biological attributes such as potential for hybridization and adaptation are important but are component factors rather than the cumulative result. They do not take into account ecological consequences associated with the introduction of the transgenic crop. These are the important issues that reflect the real outcome of introducing a particular transgenic crop.

In the interest of protecting export markets we suggest that these guidelines be expanded to require data on the ecology and ecological impact of transgenic plants and their associated herbicides. To satisfy this requirement, field data should be collected under realistic crop-pasture management conditions through a number of generations and seasons to address concerns relating to bio-safety and their effect on agro-ecological systems.

The responsibility of data collection and field evaluation for bio-safety and ecological implications of herbicide tolerant crops, must rest with the developers and not with the public sector. Suggested criteria for assessing the ecological implications of introduction of herbicide tolerant crops into cropping systems are:

Biological and environmental safety

- Risk of transfer of herbicide resistance genes to weedy relatives through out-crossing.
- Risk of herbicide residue in produce or change in the quality of the product.
- Increased levels of residues in soil, surface and/or ground water.
- Impact on the overall amount of herbicide used in the weed control program.
- Contribution to an integrated weed management program.
- Effect on adoption of reduced tillage and crop residue management practices.

Weed population ecology

- Effect on the botanical composition of the weed flora by selection through repeated application of the same herbicide or chemical group with respect to development of herbicide tolerant or resistant populations.
- Impact on desirable crop/pasture rotation options through herbicide effects on weed populations or through carry-over of residues in soil.
- Effect on opportunities for new or alternative crops.
- Effect of control of volunteer crop as a weed in subsequent fallows or crops.
- Effect on the diversity of herbicides/herbicide groups used in the rotation.
- Ability to control herbicide resistant weeds.
- Options for rotating herbicide chemical groups to avoid development of herbicide resistance.

We recommend that these criteria be incorporated into GMAC guidelines to assess the safety aspects and environmental acceptability of transgenic crops, and their contribution to integrated weed management and sustainable farming systems. Clearance for transgenic herbicide tolerant crops should be administered jointly with the National Registration Authority and the Environment Protection Authority and used to assess the safety aspects and environmental acceptability of transgenic crops, and their contribution to integrated weed management and sustainable farming systems.

An alternative recommendation, which may better serve the long term interests of farmers and the environment, would be for the developers of herbicide tolerant crops to work directly with agribusiness, farmers and environmental managers to develop a voluntary code of best management practices. A model for this is ISO 14004 (Anon. 1995), which provides guidelines to developing environmental management systems that might be adapted to provide accreditation for the use of herbicide tolerant crops.

ACKNOWLEDGMENTS

Support of the authors' work by Grains Research and Development Corporation is gratefully acknowledged.

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