REVIEW

Cultivation of Herbicide Resistant Crops: Weed Management and Environmental Aspects

KARL HURLE[1] *and JAN PETERSEN*[2]

[1]*Hohenheim University, Institute of Phytomedicine, Weed Science Department, Stuttgart;*
[2]*Institute of Sugar Beet Research, Göttingen, Germany*

Abstract

HURLE K., PETERSEN J. (2000): **Cultivation of herbicide resistant crops: Weed management and environmental aspects.** Plant Protect. Sci., **36**: 112–116.

Herbicide resistant crops will make weed control simpler and provide additional options which fit well in new concepts of weed control. The possible transfer of resistance genes to weedy relatives, the increased probability of selecting herbicide resistant weeds and the problem of volunteers need to be considered in the management of weeds, especially if such crops gain large acreages and only few compounds are used/available. For these reasons and reasons of environmental contamination with herbicides it is important that the farmer does not depend on an one-herbicide-only-control-strategy.

Key words: herbicide resistant crops; weed control; environment; outcrossing

Today, the use of herbicides is by far the most widely used method of weed control in developed countries, and has replaced to a large extent other control methods. But also in less developed countries, chemical weed control is gaining more and more of importance. The reasons are: with herbicides large acreages can be handled in a minimum of time at reasonable costs. Further, there are solutions available for most of the weed problems in all major crops, and, very important, in most cases herbicides work reliably, so the farmer can depend on it.

The herbicides presently used for weed control in crops are selective herbicides, i.e., they kill weeds and are safe to the crop. The selectivity of such herbicides often is limited to one crop or group of crop species and is based on natural tolerance of the crop(s) to the specific herbicide. However, this tolerance is not necessarily a common characteristic throughout the crop species, but can differ between cultivars, and thus limit the use of the compound. In general the efficacy of selective herbicides is not broad spectrum, i.e. depending on the compound certain weed species are not controlled. With the new technology of herbicide resistant crops (HRCs), a herbicide can be used in crops which have no natural tolerance but have been made resistant to the herbicide. This approach is mainly used for non-selective compounds in order to have a broader spectrum of weed control. The main difference between the conventional herbicide concept and the HRC-technology is that with the conventional concept an adequate crop safety for the herbicide has to be optimized in the screening process, while with the HRC-technology a target crop is tailored to the herbicide and usually achieved by means of genetic engineering. With this approach herbicide producers and seed companies are trying to expand their respective market share.

At present the non-selective herbicides glyphosate and glufosinate are the dominating compounds in this respect. For glyphosate, resistant varieties of soybeans, cotton and canola, and for glufosinate of maize and canola are already available, respectively. Further resistant varieties are being developed as for oilseed rape, sugar beet and rice. It is quite clear that there is an enormous potential for this technology, and the rapid increase in acreage of herbicide resistant crops is evidence enough for the acceptance of this technology by the farmers. However, there is still an ongoing debate on the pros and cons of this new tool in weed control.

In the following the consequences of HRCs for weed control and the environment will be discussed.

Weed control in HRCs: What is the difference to conventional chemical control?

In general it is expected that with HRCs weed control will be simpler and more advantageous than with the conventional chemical control. The main reasons for that are:

- Weed species which either can not be controlled effectively with the conventional system or only with additional efforts, e.g., herbicide mixtures, may not anymore be considered as problem weeds. This includes also parasitic and crop related weeds.
- With conventional weed control a proper timing of the herbicide application is essential, otherwise control efficacy is reduced and/or the crop is damaged. With HRCs the herbicide can be used at any growth stage which provides more flexibility in timing. This can be crucial if e.g., unfavourable weather conditions delay the herbicide application.
- Weeds which have become resistant to conventional herbicides can be controlled with the corresponding HRC-herbicide. HRCs thus provide an additional tool in the management of herbicide resistant weeds.
- Although conventional herbicides are considered as selective, their selectivity usually is not complete, i.e., the crop may suffer somewhat from the herbicide which can result in lower yields. With HRCs there is a potential for further improved selectivity and ultimately higher yields.
- With conventional weed control in some crops pre-emergence herbicides still have to be use as post-emergence compounds are not available, and therefore economic thresholds can not be applied. With HRCs the herbicide is used post-emergence and the control decision can be based on economic thresholds.
- It is expected that the HRC-technology will contribute to further develop reduced tillage and no-till systems, since weed control and mulch management will be easier and more effective (AMMON *et al.* 1995). This could substantially help to reduce soil erosion which is one of the biggest problems in world agriculture.
- An aspect, one has not paid enough attention to, partially because it is difficult to practice in conventional weed control, is the concept of pericd thresholds. With period thresholds, weeds are controlled at the time when they interfer with the crop and cause damage (critical period). At present the timing of the herbicide application is determined mainly by the growth stage of the crop and weeds, irrespective of the critical period. Due to a more flexible timing, HRCs will facilitate control according to period thresholds. Period thresholds have already been developed for some major crops as maize (KOCH & KEMMER 1980; ZIMDAHL 1988), sugar beets (SCOTT & MOISEY 1972; DAWSON 1986), rice, soybeans and vegetables (ZIMDAHL 1988).
- The new future-oriented development of precision weed control which takes in account the spatial variability of weeds *via* patch treatment or sensor driven systems, could promote HRCs and *vice versa* (HURLE & KUNISCH 1997; HURLE & WALTER 1998).

In summary: In comparison to conventional chemical weed control the HRC-technology offers some additional benefits and fits quite well in new concepts and developments in weed management. Provided this technology is cost-effective, it could replace conventional systems to a great extent.

What are the risks?

Outcrossing of the herbicide resistance gene(s): A problem for the environment or the farmer?

Lateral gene transfer, i.e., hybridization *via* pollen between related plant species or between different varieties of the same species, is a common natural process. In plant breeding this can be a problem which breeders take into account in their breeding program. It has been demonstrated that in absence of a specific herbicide selection pressure, plants with a herbicide resistance gene showed no greater fitness than plants without this gene (CRAWLEY *et al.* 1993; KAREIVA *et al.* 1996; THILL 1996). Such plants are not weedier and more invasive than susceptible biotypes, and are no super weeds. Nevertheless it is important to know which species can hybridize with a herbicide resistant crop, as the outcrossing of herbicide resistance is a new way in creating herbicide resistant weeds.

A lot of research has been done during the last few years in order to find wild plant species which are able to hybridize with transgenic crops under field conditions. Table 1 presents some examples for relevant crop-weed combinations which produce viable and fertile F_1 generations. However, the probability of the occurrence of F_1 generations is very low. In addition, the survival rate of the hybrids is reduced and only a small percentage is able to reproduce. This applies also to hybrids of crops and their non-weedy wild relatives which *per se* are not of an agricultural importance (for an overview see KEELER *et al.* 1996). Although until now not all hybridization partners are investigated, the chance for crop-weed hybrids to appear as herbicide resistant weeds seems to be rather small. If crop-weed hybrids do appear it will reduce the advantages of HRCs, and we end up in a situation comparable to the conventional chemical weed control, where close relatives of the crop usually can not be controlled by selective herbicides either. So far we have no experience of how much of an agronomic problem outcrossing of herbicide resistance genes to wild relatives might be, and to what extent it will interfere with the HRC-concept.

In this context it is worth mentioning that for genes controlling the natural herbicide tolerance there are no reported cases of outcrossing in related weed species (DYER *et al.* 1993). The reason probably is that the natural herbicide tolerance depends on more than one gene or is cytoplasmatically controlled, and thus a gene flow *via* pollen is improbable and not possible, respectively.

In summary: There is a limited chance for outcrossing of herbicide resistance genes to wild relatives. For species which have no relevance as weeds this is neither an ecological nor an agronomical problem. Wild relatives which became resistant and are occurring in crops can not be controlled anymore with the corresponding herbicide. This will limit the advantages of the HRC-technology but does not pose a problem the farmer would not be able to handle.

Herbicide resistant weeds: An increasing problem with herbicide resistant crops?

There are three ways for herbicide resistant weeds to develop: a) selection of resistant biotypes, b) outcrossing of resistance genes, and c) survival of seeds or other propagules of resistant crops in the soil; b) and c) being specific to HRCs.

The number of weeds possessing herbicide resistance is increasing. More than 150 species are reported as resistant throughout the world (RUBIN 1996). The occurrence of herbicide resistance in weed populations is generally associated with a high selection pressure imposed by high frequency of use, high dosages, long-time use and long-lasting soil activity of the compound. Out of these factors, the repetitive use is the main cause for the selection of insensitive, i.e., resistant biotypes. In principle the selection pressure in HRCs is not bigger than with conventional chemical weed control. However, it will be increased if in a crop more than one treatment is needed to obtain sufficient control, and/or several HRCs resistant to the same herbicide are cultivated on a farm. Furthermore the frequent use of a herbicide usually leads to a shift in the weed flora towards such species harder to control. In order to get these plants controlled, farmers often increase the herbicide dose, and thereby also increase the selection pressure. However, not all herbicides have the same potential for selecting resistant weed biotypes, and it is not possible to predict reliably how long a compound can be used in a field until resistant biotypes will occur (SUBRAMANIAN *et al.* 1996; HEAP 1997).

Although the possibility of outcrossing of the resistance gene(s) to wild relatives is generally considered to be low (see above), it contributes to the occurrence of resistant species.

Crops can infest subsequently planted crops if their propagules get into the soil and develop into plants. Such volunteer plants are considered weeds. Some are posing real problems as e.g., maize in soybeans, oilseed rape in sugar beets, and small grains in oilseed rape. A more serious volunteer problem could result from the transfer of the resistance trait to the same crop species especially if the recipient variety is resistant to another herbicide (multiple intraspecific resistance). This could happen with neighbouring fields of easily hybridizing crop species. Then the volunteers would be resistant to two herbicides. If herbicide resistant volunteers develop into a weed problem they need special consideration for their control, which in turn will increase the costs. To avoid these problems farmers have to make sure not to use different herbicide resistant crops with resistance to the same herbicide in crop rotations.

Finally, there are many possibilities for an unintentional distribution of seeds of HRCs e.g., by agricultural ma-

Table 1. Possible partners for hybridization between crops and weedy relatives

Crop	Weedy relatives	Reference
Oat (*Avena sativa* L.)	Wild oat (*Avena fatua* L.)	DYER *et al.* (1993)*
Oilseed rape (*Brassica napus* L.)	Turnip (*Brassica rapa* L.)	DOWNEY (1992)
	Chinese mustard (*Brassica juncea* (L.) Czern.)	DOWNEY (1992)
	Hoary mustard (*Hirschfeldia incana* (L.) Lagreze-Fossat)	DARMENCY *et al.* (1995)
	Wild radish (*Raphanus raphanistrum* L.)	DARMENCY *et al.* (1995)
	Wild mustard (*Sinapis arvensis* L.)	LECKIE *et al.* (1993)
	Dog mustard (*Erucastrum gallicum* O.E. Sch.)	CHEVRE *et al.* (1997)
Rice (*Oryza sativa* L.)	Red rice (*Oryza rutipogon* Griff.)	DYER *et al.* (1993)*
Sorghum (*Sorghum bicolor* (L.) Moench)	Johnsongrass (*Sorghum halepense* (L.) Pers.)	DYER *et al.* (1993)*
Sugar beets (*Beta vulgaris* ssp. *rapacea* (L.) Döll)	Wild beet (*Beta vulgaris* ssp. *maritima* (L.) Arcang.)	BOUDRY *et al.* (1993)
Sunflower (*Helianthus annuus* L.)	Bolander's sunflower (*Helianthus bolanderi* A. Gray)	HEISER (1976)
	Prairie sunflower (*Helianthus petiolaris* Nutt.)	HEISER (1976)
Wheat (*Triticum aestivum* L.)	Wild wheat (*Aegilops cylindrica* L.)	MALLROY-SMITH (1996)

*Review

chinery to uninfested fields, where these volunteers could create a problem if another HRC resistant to the same herbicide is cultivated. Oilseed rape could serve as a good example for unintentional distribution, since under practical conditions it is not very likely for the farmer to spend enough time for cleaning the combine from the small seeds of this crop.

It seems that in this context volunteers will be the main agronomic problem, followed by the "normal" selection of herbicide resistant weeds, and the emergence of herbicide resistant wild relatives by hybridization.

In summary: It is very likely that with HRCs herbicide resistant weeds, including resistant volunteer crops, will be an increasing problem. To avoid this problem the farmer must be aware of the possible risks, and take them into account in his weed management strategies. The main strategic element must be an appropriate crop and herbicide rotation.

Increased use of HRCs: A herbicide problem for the environment?

Due to the very high registration standards for pesticides, only environmentally benign compounds get on the market, and the specific herbicides for HRCs are no exception. However, there is a correlation between the intensity a compound is used and the probability of the compound to become conspicuous in the environment e.g. in ground, surface and rainwater and the atmosphere. In the context with HRCs this could be the case if for a single herbicide several major resistant crops are available, and farmers plant the crops and use the herbicide on large scale, because the system is cost-effective and provides good weed control. Atrazine is an example for it. But it could apply also for environmentally safer compounds if they were used year after year on large scale, and therefore finally do not meet the safety standards set by the society anymore (HURLE 1996). From this point of view it is highly desirable not to depend too much on a one-herbicide-only-strategy.

In summary: With HRCs there is a risk for environmental problems if the system depends on a single/few herbicide(s) and such crops are cultivated on large areas.

Conclusions

Until now there is no long-term experience with HRCs. While the advantages for weed control are quite obvious, the risks in connection with hybridization, selection of herbicide resistant weed species and volunteers, and environmental contamination are clear in theory, but need to be confirmed under practical conditions in order to obtain a real estimate of the risk imposed by HRCs to cropping systems and the environment. It seems quite clear that the risks increase with the extent a HRC is cultivated and the corresponding herbicide is used. Besides careful consideration of the possible risks involved with the introduction of HRCs during registration, it is recommended to follow HRC-systems in a post-registration monitoring program in order to take action if necessary. This new technology requires more strategic planning of the management of weeds and of cropping systems in general. Especially for developing countries with less experience in chemical weed control this could be a crucial point.

References

AMMON H.U., GARIABAY S., BOHREN C. (1995): The use of dead or living mulch in maize and its suppression with herbicides. 9th EWRS Symp., Budapest: 527–534.

BOUDRY P., MÖRCHEN M., SAUMITTOU-LAPRATE P., VERNET P., VAN DIJK H. (1993): The origin and evolution of weed beets: consequences for the breeding and release of herbicide-resistant transgenic sugar beets. Theor. Appl. Genet., **87**: 471–478.

CHEVRE A. M., EBER F., BARANGER A., RENARD A. (1997): Gene flow from transgenic crops. Nature, **389**: 924.

CRAWLEY M. J., HAILS R. S., REES M., KOHN D., BUXTON J. (1993): Ecology of transgenic oilseed rape in natural habitats. Nature, **363**: 620–623.

DARMENCY H., FLEURY A., LEFOL E. (1995): Effect of transgenic release on weed biodiversity: Oilseed rape and wild radish. In: Brighton Crop Protect. Conf.–Weeds, 2: 433–438.

DAWSON H. J. (1986): The concept of period thresholds. In: Proc. EWRS Symp., Economic Weed Control: 327–331.

DOWNEY R. K. (1992): Biosafety of transgenic oilseed *Brassica* species. In: The biosafety results of field tests of genetically modified plants and microorganisms. Int. Symp., Goslar, BBA, Braunschweig: 17–21.

DYER W.E., HESS F. D., HOLT J. S., DUKE S. O. (1993): Potential benefits and risks of herbicide-resistant crops produced by biotechnology. Hort. Rev., **15**: 367.

HEAP I. M. (1997): The occurrence of herbicide-resistant weeds worldwide. Pesticide Sci., **51**: 235–243.

HEISER C. B. (1976): Sunflowers (*Helianthus – Compositae*). In: SIMMONDS N. W. (Ed.): Evolution of Crop Plants. London, Longmans Press.

HURLE K. (1996): Weed management impact on the abiotic environment in particular on water and air quality. In: 2nd Int. Weed Control Congr., Copenhagen: 1153–1158.

HURLE K., KUNISCH M. (1997): Sensor driven weed control – concepts and perspectives. In: 10th EWRS Symp., Poznan: 136–140.

HURLE K., WALTER H. (1998): Past, present and future of weed science. Meded. Fac. Landbouw. Rijksuniv. Gent (in press).

KAREIVA P., PARKER I. M., PASCUAL M. (1996): Can we use experiments and models in predicting the invasiveness of genetically engineered organisms? Ecology, 77: 1670–1675.

KEELER K. H., TURNER C. E., BOLICK M. R. (1996): Movement of crop transgenes into wild plants. In: DUKE S. O. (Ed.): Herbicide-Resistant Crops. Boca Raton, CRC Press, Inc., Lewis Publ.

KOCH W., KEMMER A.(1980): Schadwirkung von Unkräutern gegenüber Mais in Abhängigkeit von Konkurrenzdauer und Unkrautdichte. Meded. Fac. Landbouw. Rijksuniv. Gent, **45**: 1099–1109.

LECKIE D., SMITHSON A., CRUTE I. R. (1993): Gene movement from oilseed rape to weedy populations – a component of risk assessment for transgenic cultivars. Aspects Appl. Biology, **35**: 61–66.

MALLROY-SMITH C. A. (1996): Gene transfer between wheat and *Aegilops cylindrica*. In: 2nd Int. Weed Control Congr., Copenhagen: 441–445.

RUBIN B. (1996): Herbicide-resistant weeds – the inevitable phenomenon: mechanisms, distribution and significance. Z. PflKrankh. PflSchutz, Sonderh., **XV**: 17–32.

SCOTT R. K., MOSEY F. R. (1972): The effect of weeds on the sugar beet crops. In: Proc. 11th British Weed Control Conf.: 491–497.

SUBRAMANIAN M., BERNASCONI P., HESS F. D. (1996): Approaches to assess the frequency of resistance development to new herbicides. In: 2nd Int. Weed Control Congr., Copenhagen: 447–453.

THILL D.C. (1996): Managing the spread of herbicide resistance. In: DUKE S. O. (Ed.): Herbicide-Resistant Crops. Boca Raton, CRC Press, Inc., Lewis Publ.

ZIMDAHL R. L. (1988): The concept and application of critical weed-free period. In: ALTIERI M. A., LIEBMAN M. (Eds.): Weed Management in Agroecosystems: Ecological approaches. Boca Raton, CRC Press: 145–155.

Abstract

HURLE K., PETERSEN J. (2000): **Pěstování plodin rezistentních vůči herbicidům – ochrana proti plevelům a otázky životního prostředí**. Plant Protect. Sci., **36**: 112–116.

Plodiny rezistentní vůči herbicidům zjednoduší regulaci plevelů a poskytnou další možnosti, které jsou v souladu s novými směry v hubení plevelů. Možný přenos genů rezistence mezi příbuznými plevely, zvýšená pravděpodobnost selekce plevelů rezistentních vůči herbicidům a problém výdrolu rezistentních plodin musí být zvážen při regulaci plevelů, obzvláště pokud takové plodiny zaujímají velké plochy a je možné použít úzké spektrum účinných látek. Z těchto důvodů a z důvodů kontaminace životního prostředí herbicidy je důležité, aby pěstitel nebyl závislý na použití jediného herbicidu.

Klíčová slova: plodiny rezistentní vůči herbicidům; regulace plevelů; životní prostředí; křížení

Corresponding author:

Prof. Dr. KARL HURLE, Hohenheim University, Institute of Phytomedicine, D-70593 Stuttgart, Germany, tel.: + 49 711 45 92 399, fax: + 49 711 45 92 408, e-mail: khurle@uni-hohenheim.de