Plant Biotechnology: Potential Impact for Improving Pest Management in European Agriculture

Oilseed Rape – Herbicide-Tolerant Case Study

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Introduction

Oilseed rape is an important crop in the European Union, harvested on 3.0 million hectares with a production value of €2.5 billion. Three countries (France, Germany, U.K.) account for 90% of the rapeseed production in the E.U. Table 1 summarizes rapeseed production statistics for the major E.U countries and U.S. for 2001. Oilseed rape is called "canola" in the U.S.

Rapeseed oil is usually blended with other vegetable oils for the production of various cooking oils, margarines, and salad dressings. After the rapeseed oil has been pressed out, the solid remains of the rapeseed are used as an animal feed.

The E.U. annually produces 5.1 billion kilograms of meal and 3.6 billion kilograms of oil from rapeseed [4].

During the 1970s, there was a rapid increase in the production area of winter oilseed rape in northern Europe. The European community heavily supported this crop to develop domestic vegetable oil production in Europe [11].

European production of rapeseed plays an important role in increasing E.U. self-sufficiency in cooking oil production and contributes to limiting European imports of meal for animal feed.

Oilseed rape belongs to the family cruciferae, the members of which are referred to as brassicas. The name rape originated from Latin word "rapum" which means turnip. Rape was first cultivated in Europe in the 13th century but then suddenly faded out of production. Reintroduced in the 19th century, oilseed rape has now become Europe's most important oilseed crop.

The Dutch, whose engineers used rape oil to work pumps for draining swamps, first introduced rape to the U.K. in the 19th century. The advent of petroleum oils led to a decline of oilseed rape production until the 1960s. Oilseed rape has enjoyed unprecedented popularity since 1973, when a significant increase in commodity prices and support from the Common Agricultural Policy (CAP) raised the price of rape to a sufficiently high level, prompting farmers to grow it [1]. Moreover, the development of canola varieties with low erucic acid and glucosinolate levels in 1970s through advances in conventional breeding further led to increased plantings. Erucic acid imparts anti-nutritional properties to oil while glucosinolate in oilseed rape meal is toxic to livestock.

Oilseed rape is planted in both spring and winter months in Europe. Spring oilseed rape is predominantly a crop of northern regions of the U.K., Germany, and France where cold, damp weather prevails. Winter oilseed rape is a crop of western Europe where mild winters dominate. More than 75% of oilseed rape in the U.K. is sown in autumn and is referred to as winter oilseed rape. Growers prefer winter oilseed rape to the spring crop due to its excellent fit with winter cereals and its higher yield potential [2]. Winter oilseed rape is planted beginning in late August and is harvested in July of the following year [24]. The crop goes into a vegetative stage over winter and flowers in spring.

Weeds as pests of winter oilseed rape

Oilseed rape is a slow-growing crop. Consequently, rapeseed is very sensitive to weed competition, especially during the early stages of development. Spring-planted rape is more sensitive to weed competition than the winter-planted crop, due to its shorter growing season during drier summer months.

Weeds that germinate in autumn are the main problem in winter oilseed rape as the crop is planted during that time. Some weeds such as chickweed, speedwells, and cleavers, grow at lower temperatures and threaten to smother the oilseed rape crop in early spring [15].

In general, weeds in the winter oilseed rape fields of Europe are volunteer cereal grasses and botanically similar, closely related brassica weeds (example: charlock, wild mustard, stinkweed, shepherd's purse, ball mustard, flixweed, wormseed mustard, and hare's-ear mustard). Since the planting of oilseed rape follows the harvest of winter cereals, cereal seeds left on the soil surface at harvest germinate as volunteers and pose problems in the oilseed rape [3]. Volunteer cereal weed problems are particularly severe if the crop is planted using no-till or reduced-tillage methods.

Cleavers may reduce yield by 10%, growing at densities up to 10/m^2, and may be even more damaging in early season crops. Conversely, volunteer cereals are more damaging in late season crops [19].

A 1989 large-scale survey of winter oilseed rape to assess weed distribution in U.K. fields showed that common chickweed, mayweeds, and common-field speedwell were the most abundant broadleaved weeds. Cleavers, field pansy, shepherds' purse, ivy-leaved speedwell, charlock, and common poppy were less frequent [2][15]. Besides volunteer cereals such as wheat and barley, annual meadowgrass is the most frequently recorded grass weed.

Rapeseed is seeded at a density of 80-100 plants per square meter. Emerged weed infestations in a natural setting can reach 120 seedlings per square meter. Volunteer grass densities exceeding 800 plants/m^2 are common in the oilseed rape fields of the U.K. [3][15]. Grass weeds of minor importance are oats, ryegrass, annual meadowgrass, barren brome, witchgrass, and blackgrass. Overall, of the weeds that infest winter oilseed rape in the U.K., volunteer cereals and chickweed are the most frequent; volunteer cereals and cleavers are the most competitive; and blackgrass, wild oats, charlock and hogweed are the most difficult to control weeds [12]. On the other hand, weeds that emerge in spring such as knotgrass, red shank, and fat hen and weeds with no specific emergence patterns such as common chickweed and annual meadowgrass dominate spring planted oilseed rape in the U.K.

Weeds noted in oilseed rape fields of France and Germany are the same as those in the U.K. [3][15]. A 1977 survey indicated that blackgrass is the most frequent grass weed in France, followed by volunteer cereals (mainly barley), annual meadowgrass, wild oats, sterile oats, Italian ryegrass, rough bluegrass, and quackgrass [13]. Based on crop yield loss estimates, it was found that cleavers is the most competitive oilseed rape weed in Germany followed by common chickweed, and red deadnettle. Other common weeds such as mayweeds, field pansy, forget-me-not, shepherd's purse, and annual meadowgrass are equal in their competitiveness [15].

Weeds have a major negative impact on oilseed rape through competition for shared resources such as water, nutrients, sunlight, and space, reducing crop yields. The mean density of common chickweed needed to cause 5% yield losses was determined to be 37 plants per square meter [5]. A 5% yield loss figure is given as an economic threshold above which a treatment is worthwhile in oilseed rape [15].

Modeling studies conducted in France and Germany indicate that grass weeds and volunteer cereals exceeding a density of 30 plants/m^2 cause an 8% yield reduction in oilseed rape with losses increasing if the crop is planted late [3][4]. 200 volunteer barley plants/m^2 reduced UK oilseed rape yields by 16% in three studies, while yield reductions were 39% to 78% at double this density in another study [7].

Several researchers confirmed that early-planted oilseed rape tolerate heavy weed pressure without considerable yield loss [3][4][9]. Volunteer barley at 100 plants/m^2 caused a 23% yield reduction in an early-planted crop, while yield losses were up to 43% in the late plantings. An early-planted crop has a competitive advantage over weeds as fewer weeds germinate at the time of early crop planting than at late planting. For example, August planted oilseed rape competes with fewer autumn weeds like chickweed than a September-planted crop.

Besides reducing yield, late-maturing and tall weeds such as cleavers reduce harvest efficiency. Weeds like common chickweed act as hosts for oilseed rape diseases such as gray mold and Sclerotinia stem rot [15]. The importance of volunteer cereals, barley for example, in vectoring aphids that carry barley yellow dwarf virus to other cereals is widely recognized.

Weed seed contamination is a major issue in harvested oilseed rape as loads containing greater than 2% contamination are rejected in Europe [3]. Weeds that are in the same family as oilseed rape such as charlock and wild radish degrade the quality of oil with their high concentrations of erucic acid and glucosinolate. As a result, the permissible level of weed seed contamination from plants belonging to the same family as oilseed rape is set at 0.1% [15]. Weed seed contaminants are potentially expensive to clean to clean from harvested oilseed rape (more than £10/metric ton) [15]. The need for low levels of contamination by brassica weeds in harvested oilseed rape necessitates effective weed control.

Weed management in European oilseed rape

While cultivation for weed control is not feasible in a broadcast crop, a drill-seeded crop planted in wide rows offers the possibility for cultivation. However, cultivation is not an option in winter oilseed rape due to wet ground conditions. Stubble burning as a means to manage weeds has been banned in most of Europe [15]. In Scotland, where stubble burning is still legal, this technique is useful in reducing the number of grass weed seeds lying in the stubble from the previous crop [15]. The most widely used method to control weeds in oilseed rape fields is the use of herbicides. About 94% of oilseed rape acreage in the U.K. was treated with herbicides in 1998, while 99% were treated in France in 1997 [18][23]. In a 1994 report, 21% of the variable costs (equivalent to £45/ha) in oilseed rape production were attributed to herbicides [4].

A wide range of herbicides categorized as soil-applied residual herbicides, selective post emergence (POST) herbicides for broadleaf control, and selective grass herbicides are currently available for weed control in oilseed rape. Metazachlor, trifluralin, propachlor, tebutam, and napropamide are soil-applied residual herbicides. Metazachlor is a broad-spectrum herbicide with activity against both grasses (such as blackgrass, wild oats, and meadowgrass) and several broadleaf weeds. It can be applied both as a pre emergence (PRE) or POST herbicide, with best activity on weeds such as poppy when applied PRE [12]. Propachlor has a similar spectrum as metazachlor but has to be applied prior to weed emergence [15]. Tebutam and napropamide are effective herbicides commonly used to broaden the spectrum of trifluralin but create carry over and rotational restrictions [15]. Because of the residual effects of trifluralin, tebutam, and napropamide, a 12-month interval is recommended before planting other crops [15].

Herbicides that are used after crop emergence include pyridate, benazolin, clopyralid, cyanazine, metazachlor, and propyzamide [6][8]. Pyridate is used only on a limited scale due to specific restrictions associated with its use. Benazolin is a broadleaf herbicide with excellent activity against cleavers and chickweed. Cyanazine is good for control of annual weeds such as meadowgrass and brassica weeds such as charlock, but is ineffective against cleavers. Clopyralid's strengths are mayweed, thistle, and groundsel control; however, it is less effective against small nettle and speedwell species [12]. These herbicides need to be combined according to the existing weed infestation to obtain a broader spectrum of control.

Dalapon and TCA were the most widely used grass herbicides in 1980s. Their use declined due to crop injury, consequent yield reduction, and the subsequent introduction of selective POST herbicides [3]. Selective grass herbicides currently being used in oilseed rape are fluazifop, quizalofop, cycloxydim, sethoxydim, and propaquizafop [12][13][15]. These products can be used at an early stage of crop growth when other herbicides such as propyzamide cannot be used due to crop injury concerns [15]. A limitation to the use of selective graminicides is the difficulty in controlling annual meadowgrass [12][15]. Cyanazine is widely used where annual meadowgrass is a problem.

Research has shown that the use of propyzamide reduces grass infestations by 97-99% [13]. Metazachlor provides 88-94% control of a wide spectrum of weed species [6].

The use of a combination of metazachlor+benazolin+clopyralid reduced the untreated percent weed cover from 29% to 1% and increased rapeseed yield by 47% [27]. In plots with high weed populations, the combination of metazachlor with propazymide or cyanazine increased rapeseed yields by 42% [29].

Metazachlor (19%) followed by propaquizafop (11%), cycloxydim (10%), propyzamide (9%), and clopyralid (7%) were the most widely used herbicides in 1998 for in crop weed control in the U.K. [18].

In 1996, the average cost of herbicides for winter rapeseed production in the U.K. was £65/ha and £40/ha for spring rapeseed [37]. The average cost for herbicides in U.K. rapeseed in 2002 was £50/ha [19].

In the U.K. in 2002, glyphosate was the most commonly used herbicide in oilseed rape (45% area treated), being used as both a pre-drilling cleanup and a pre-harvest dessicant [30]. Propaquizafop was used on 36% of the acreage for grass weed control and volunteer cereal control [30]. Metazachlor was used on 30% of the acres primarily for control of broad-leaved weeds [30]. The average U.K. oilseed rape acre was treated with three herbicides in 2002. In the U.K. in 2002, 564 metric tones of herbicides were used on the nations 419,000 hectares of oilseed rape (1.35 kg/ha) [30]. In the U.K. between 1992 and 2002, the rate of herbicide application increased by 17%.

Metazachlor is the most widely used herbicide in German winter oilseed production, with approximately 80 to 90% of the area sprayed [17]. The most common program in Germany is the use of metazachlor (0.75 kg/ha) in combination with quinmerac (0.25kg/ha) at a cost of approximately €80/ha [25]. A follow-up treatment is applied in the early spring as needed and may be comprised of a POST application of a broadleaf herbicide or a grass herbicide, or both depending upon the weed spectrum [23]. In 1997, trifluralin was applied to 54% of oilseed rape acreage in France followed by tebutam + clomazon (43%), metazachlor (29%), and metazachlor + quinmerac (9%) [23]. In 2001 in France, oilseed rape growers typically used one of 5 herbicide programs for weed control. The average use rate of herbicides in France on oilseed rape hectares was 1.7 kg/ha [31]. Trifluralin and metazachlor were the most widely applied active ingredients.

Currently, the program approach for weed control in winter oilseed rape in Europe, and particularly in Germany and the U.K., is a combination of metazachlor + Quinmerac applied either PRE or early POST [15][17][24]. Quinmerac is a broadleaf herbicide with specific activity against cleavers [24]. Overall, herbicide programs in European oilseed rape consist of three herbicides applied in two or three treatments [18].

The average cost of weed control for rapeseed in France is between €60 and €120/ha, but can be as high as €150/ha in some difficult situations [44]. This is the largest expense for oilseed rape production, accounting for one-third of total operational expenses.

Popular herbicide programs for broadleaf weed control in the 1980s in the U.K. were a PRE application of metazachlor followed by a sequentical POST application of the same chemical or a POST tankmix application of metazachlor + benazolin + clopyralid, or a PRE application of metazachlor followed by benazolin + clopyralid POST [6][8][10]. Crop injury is an issue with benazolin + clopyralid combinations. In recent years, metazachlor (1.25 kg ai/ha) as PRE or early POST followed by a POST graminicide application (such as cycloxydim at 0.2 kg ai/ha) has become the common herbicide program in the U.K. An alternative program being used in the U.K. when herbicide-resistant weeds are an issue is the POST application of propyzamide (0.7 kg ai/ha). Unfortunately, weed control from propyzamide-based programs is not complete, as it does not control all broadleaf weeds.

Chemical control of oilseed rape weeds is difficult for several reasons. While cleavers, hemlock, and brassica weeds are the most difficult weeds to control in oilseed rape, brassica weeds pose particular control difficulty as they belong to the same family as oilseed rape.

Several problems plague weed management in European oilseed rape. The extensive use of grass herbicides such as diclofop and fenoxaprop in wheat and other herbicides in the same family such as quizalofop, fluazifop, sethoxydim, and cycloxydim in oilseed rape rotations has led to the development of resistance among weeds such as blackgrass, ryegrass, and wild oats in France and the U.K. [16]. As a result, herbicide choices available for the control of volunteer cereals, the most competitive weeds in oilseed rape, are limited. Moreover, with the phase out of cyanazine and benazolin herbicides in the E.U. beginning in 2003, oilseed rape growers in countries such as the U.K. have few POST broadleaf herbicides available for their use. The withdrawal of cyanazine is a problem for the control of volunteer spring oilseed rape in winter oilseed rape production [15]. The use of propyzamide and clopyralid, the two available POST broadleaf herbicides, is projected to increase in response to the withdrawal of the above herbicides. However, propyzamide and clopyralid have a narrow spectrum of activity and may not provide adequate control of weeds.

In some areas of Germany, the cropping of oilseed rape is effectively restricted by the increasing occurrence of hedge mustard. Field pansy and shepherds purse are becoming increasingly troublesome due to the absence of effective herbicides [17].

Current losses in rapeseed yield in France due to weeds are estimated at 15% [42].

<u>Transgenic herbicide-tolerant oilseed rape</u>
Two herbicide-tolerant oilseed rape systems has been developed in Europe, glufosinate-tolerant or LibertyLink (LL) and glyphosate-tolerant or RoundupReady (RR). Belgium-based Plant Genetic Systems (formerly owned by Aventis, now Bayer CropScience) developed the first transgenic LL oilseed rape while Monsanto developed RR varieties.

Modification of oilseed rape with genes that encode for resistance to glufosinate and glyphosate has led to the development of LL and RR varieties, respectively. Glufosinate tolerance is the result of the introduction of gene that codes for the enzyme phosphinothricin-N-acetyltransferase (PAT) isolated from a soil bacterium to the oilseed rape genome. The PAT enzyme catalyzes the acetylation of phosphinothricin, detoxifying glufosinate into an inactive compound. Glyphosate inhibits the synthesis of aromatic amino acids by blocking the enzyme 5-enolpyruvylshikimate-3-phosophate synthase (EPSPS). Genetically modified oilseed rape was developed through genetic substitution of EPSPS with an altered EPSPS enzyme, which is not affected by glyphosate.

The biotech herbicide-tolerant canola varieties were commercialized in Canada in 1996 and in the U.S. in 1999. Approximately 65% of U.S. canola acreage is planted with biotech varieties, while in Canada 55% of canola acres are biotech [45][46].

A recent report analyzing the effects of biotech canola in Canada reported that there was a yield increase of 10% with an profit increase of $11.58/A ($ Canadian) or €7.64/ha [45]. The report estimated a reduction of 6,000 tons of herbicides as a result of using the transgenic canola (1.8lb/a) (2.02kg/ha).

In the U.S., it is estimated that canola growers are saving $12.65/A as a result of lower weed control costs with herbicide tolerant varieties [47]. Average yield increases are estimated at 6% in the U.S. [47].

LibertyLink oilseed rape has been submitted for regulatory approval for cultivation in France, U.K., Germany, and Belgium. Consents were issued for planting in U.K. and France in 1996 and 1998, respectively, while the decision is pending on Germany and Belgium due to the de facto moratorium that has been in place since 1998.

Transgenic oilseed rape has been evaluated in grower fields in the U.K. since 1998 [14]. Field evaluations in France of single and sequential applications of glyphosate and glufosinate on glyphosate- and glufosinate-tolerant winter oilseed rape, respectively, were conducted for three seasons starting in 1995/96. These evaluations showed that with transgenic programs, crop injury was minimal and weed control was equal or superior to conventional herbicide programs [22].

Glufosinate was the most consistent performing herbicide over a range of sites and years and was the only treatment to return a positive margin over herbicide cost [41].

At one site, the application of traditional residual herbicides gave a 40% increase in rapeseed yield compared with the untreated plots, while a yield increase of 72% was seen following the application of glufosinate [41].

A three-year set of Farm Scale Evaluations (FSEs) was conducted in the U.K. to compare genetically modified herbicide tolerant (GMHT) crops with conventional varieties. The GMHT rapeseed in the FSEs was tolerant to glufosinate. The FSEs compared the level of weed control and herbicide use amounts between the GMHT plots and plots planted with conventional varieties. The herbicide use amount did not differ significantly between the GMHT (1.334kg/ha) and the conventional crop (1.445 kg/ha) [38]. The FSEs determined that glufosinate treatments were more effective in controlling weeds in the GMHT plots than were the herbicide treatments used with the conventional varieties [39]. The final number of weed seedlings was 22% higher in the conventional plots than GMHT plots, while weed biomass in the conventional plots was 2.9 times the amount of weed biomass in the GMHT plots [39].

Experiments in the U.K. have demonstrated that a single application of glufosinate can provide 90-100% control of important broadleaf and grass weeds [40]. By comparison, conventional herbicides sometimes provide 55-67% control because seasonal low soil moisture can negatively affects the performance of residual herbicides [40].

A participant in the FSE trials in Scotland estimated that the GMHT oilseed rape was £84/ha cheaper to grow than conventional varieties [14].

A 4% average yield advantage for glufosinate was observed in a 2 year U.K. experiment [43].

Recent U.K. farm level field trials conducted in 2002 have shown yield gains of 14% for GM herbicide tolerant winter oilseed rape and 22% for spring oilseed rape [28]. In 2001, the yield gain for GMHT oilseed rape was estimated to be about 9% [28].

<u>Impacts</u>

An empirical investigation of the potential adoption of glyphosate-tolerant oilseed rape in France by INRA suggested that transgenic oilseed rape growers would be able to save €25/ha on herbicide costs [21]. INRA's report concluded that transgenic oilseed rape could be adopted on 75% of French oilseed rape acreage.

A recent report from CETIOM in France concluded that a decrease of about 30% in herbicide costs would be possible with the herbicide tolerant varieties [44]. The report concluded that given current practices for weed control in rapeseed the biotech varieties could include 20 to 40% of the area planted to rape based purely on technical conditions [44].

An analysis of genetically modified crops by U.K. researchers in 2002 suggested that the introduction of oilseed rape could reduce herbicide application rates by 25% and active ingredient use by 60% [26]. In addition, the potential decrease in number of spray applications was reported to be 33%. These researchers profiled the standard herbicide program in U.K. winter oilseed rape as quinmeric + metazachlor + laser + propygazate with a total use of 1.7 kg/ha [26]. The GM program was estimated to consist of two glufosinate applications totaling 0.6 kg/ha.

The average cost of a glufosinate program in rapeseed in France has been estimated at ₣440/ha (2 applications) (€67/ha) [44].

A recent study projected likely adoption of herbicide tolerant rapeseed varieties on 25% of the E.U.'s acres due to an economic advantage resulting from better weed control with higher yields and/or lower costs of weed control [20].

The substitution of two glufosinate applications for the current herbicides used in rapeseed would lower herbicide use by 12% (see Table 2). It is assumed that the cost of a glufosinate-tolerant program would be approximately €65/ha which represents an average reduction of €22/ha or a 25% reduction from current costs (see Table 3).

It is assumed that the biotech varieties would be planted 25% of the rapeseed hectares in the E.U., implying an overall reduction in herbicide use of 117 thousand kg and an annual overall saving of €14.7 million/yr.

It is assumed that the glufosinate-treated rapeseed would yield approximately 6% higher due to better weed control. The aggregate impacts of this increased yield are shown in Table 4. Assuming that Biotech varieties would be planted on 25% of the current rapeseed hectares in the EU implies a production increase of 124 million kg, with an increase in total crop value of €28 million.

Table 1a: Oilseed Rape Production			
	Area (000 ha)	***Production (billion kg)***	***Value (€ million)***
France	1083	2.9	670
Germany	1138	4.2	916
U.K.	451	1.2	265
Total E.U.	2991	8.9	2537
U.S. (Canola)	582	0.9	175

Source: [32] [33] [34] [35] [36]

Table 1b: Oilseed Rape Production			
	Area (000 A)	***Production (billion Lbs)***	***Value ($ million)***
France	2708	6.4	670
Germany	2845	9.2	916
U.K.	1128	2.6	265
Total E.U.	7478	19.6	2537
U.S. (Canola)	1455	2.0	175

Dollars and Euros assumed equivalent.

Table 2: Potential Impact on Herbicide Use of Glufosinate-Tolerant Oilseed Rape							
	Area (000 ha)	***Herbicide use rate (kg ai/ha)***		***Change in herbicide use rate (kg/ha)***	***Total herbicide use (million kg)***		***Change in herbicide use (million kg)***
		Current	*Biotech*		*Current*	*Biotech*	
France	1083	1.70	1.34	-0.36	1.84	1.45	-0.39
Germany	1138	1.40	1.34	-0.06	1.59	1.52	-0.07
U.K.	451	1.35	1.34	-0.01	0.61	0.60	-0.01
Total	2672				4.04	3.57	-0.47

Source: [23] [25] [30] [31] [38]
100% adoption assumed.

Table 3: Potential Impact of Glufosinate-Tolerant Oilseed Rape on Weed Control Costs					
	Area (000 ha)	***Weed control costs (€/ha)***		***Savings (€/ha)***	***Total savings (million €/year)***
		Conventional	*Biotech*		
France	1083	90.0	65	-25	-27.07
Germany	1138	90.0	65	-25	-28.45
U.K.*	451	72.5	65	-7.5	-3.38
Total	2672				-58.90

100% adoption assumed.
*Weed control costs in the U.K. are ₤50/ha. [19]
Sources: [25] [44]

Table 4: Potential Impact of Glufosinate-Tolerant Oilseed Rape on Oilseed Rape Production and Value		
	Production (million kg)	***Value (€ million)***
France	174	40
Germany	252	55
U.K.	72	16
Total	498	111

100% adoption assumed.
6% increase in production and value assumed.

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