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

Wheat – Herbicide-Tolerant Case Study
December 2003

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Wheat Production in the E.U.
The European Union produced a total of 92 billion kg of wheat on 17 million hectares in 2001. The contribution of the European Union's wheat to world total is 8% of area and 16% of production. Per hectare wheat yields are highest and have been increasing in the E.U.-15 compared to other important wheat producing countries in the world such as China, the U.S., and Russia (Table 1). Wheat productivity is 52% higher in the E.U.-15 compared to China, which ranks second in productivity.

France is the number one wheat producing country in the E.U., accounting for 34% of the production in 2002 (Table 2). The major wheat producing countries in the E.U. are France, Germany, United Kingdom, Italy, and Spain. These countries account for 84% of production (Table 2). The wheat crop is worth €11.1 billion/yr to E.U. growers (Table 2).

Winter wheat accounts for 100% of E.U. production. Depending on the region, winter wheat is planted in the months of October or November and harvested in late summer during the months of June, July, or August in France, Germany, U.K., Spain, and Italy.

In the mid-19th century, the area devoted to wheat in Europe was limited by the need for rotation. The opening of the prairies in the U.S. for wheat growing led to cheap grain imports into Europe. Farmers in Europe could not compete and a long agricultural depression followed.

Modern wheat production in Europe relies on effective herbicides. For the first time, effective herbicides allowed farmers in Europe to grow wheat only on land most suited for its production. No longer did crops have to be grown solely for their contribution to weed control through the rotation [34]. This has allowed farmers more freedom in the choice of crops that are best suited to their land, climate and markets [33]. Higher yields and supported prices resulted in the rapid intensification of winter wheat particularly on the heavier soils in northern Europe [34].

Effective herbicides and chemical fertilizers largely removed the need for rotations, hence avoiding crops which are only grown to 'weed and feed' wheat. This resulted in concentration of wheat growing onto land best suited to its production [35]. As a result, the unit cost of production of wheat in Europe became comparable with the U.S. and Canada [33]. The increase in yield resulted in the greater competitiveness of European wheat [35]. The tremendous increase in European wheat yields resulted from a fuller exploitation of a climate and soils that can sustain high yields [35].

Weeds as winter wheat pests
The spectrum of weeds in European wheat fields is typical of cereal cropping systems. Grass weeds commonly noted in winter wheat fields of Europe include blackgrass, wild oats, littleseed canarygrass, bentgrass, sterile brome, ryegrass, and annual meadowgrass

[5][6][8]. Cleavers, scentless chamomile, common chickweed, corn poppy, speedwells, Canada thistle, field pansy, fat hen, wild radish, wild mustard, shepherds' purse, bifora, field bindweed, hemp nettle, and polygonum species are the most widely encountered broadleaf weeds [5][6][8]. These weeds are present at various levels and pose problems at various degrees in different countries. For example, blackgrass and bentgrass are more prevalent and raise serious concerns to wheat growers in Germany, while blackgrass and oats are a major problem in U.K. Similarly, blackgrass, oats, and ryegrass are problematic in wheat production in France, while oats are troublesome to Italian wheat growers. Among broadleaf weeds, cleavers, chamomile, common chickweed, and speedwells in Germany; cleavers, chamomile, common chickweed, and fat hen in U.K.; cleavers, chamomile, speedwells, Polygonum species, and thistles in France; and chamomile and corn poppy in Italy pose more problems than any other weeds.

Most of the above weeds share the same life cycle as winter planted wheat. The consequent wheat/weed competition is intense for shared resources resulting in yield losses. Winter wheat yields were reported to decrease by 8% in U.K. with blackgrass infestations at 20/m^2 [5]. Other research in U.K. showed that the number of grass weeds (per square meter) needed to reduce wheat yields by 5% is 15 –20 blackgrass, 5 to 7 Italian ryegrass, and 3 to 5 wild oats [16]. Research indicated that uncontrolled blackgrass could reduce wheat yields by 30-67% [1].

Cleavers is the most competitive broadleaf weed in U.K. wheat [5]. As few as one cleaver plant/m^2 can reduce wheat yields by 3 to 5% [5]. Other reports from U.K. indicate that 25 cleaver plants/m^2 caused 30% losses of winter wheat yields in addition to serious contamination of harvested grain [12]. Its competitiveness mainly stems from a prolonged germination period, abundant growth late in the season (May to July), and its ability to grow above the crop canopy. On the other hand, field pansy competes poorly with wheat, causing a yield reduction of 2% at a density of 109 plants/m^2 [3].

Economic thresholds have been developed for various weed species to aid in weed management. For example, weed threshold research in Germany suggested that control practices should be undertaken when the density of loose silky bentgrass, blackgrass, cleavers, and black bindweed are 20, 20, 0.5, and 2 plants/m^2 respectively [9]. A review of field trials in Scotland conducted for ten years suggested that winter wheat yields could be improved significantly when herbicides were used to control mixed weed infestations at a density of 75 plants/m^2 [11]. Based on timing of competition, grass weeds, in general, need to be controlled in autumn or winter months while broadleaf weed control can be delayed until spring depending the competing species and their density.

Winter wild oats are the most serious and widespread grass weed in wheat in Spain. More than 27% of the acreage is considered as seriously infested [10]. In Andalusia, wild oats are found on about 65% of the wheat fields [2]. Prior to their control in the 1980s, it was estimated that wild oats reduced Spain's wheat production by 173,000 tons/yr [20].

Weed management

Initial uses of herbicides in wheat were postemergence applications of phenoxy herbicides for control of broadleaf weeds. The discovery of selective herbicides that would control grass weeds in wheat led to their widespread use beginning in the early 1980s.

Intensive wheat rotations and late plantings when soil moisture is limited were made possible in countries such as U.K. by selective herbicides. A typical weed management strategy in winter wheat across Europe consists of an autumn herbicide application for broad-spectrum weed control followed by a spring herbicide application depending on the weed species present at that time. Spring applications are mostly aimed at control of broadleaf weeds.

Blackgrass shares the same growth cycle as autumn-sowed wheat [34]. The introduction of chlorotoluron and isoproturon in the early 1970s provided very high level of blackgrass control [34]. Thus, winter wheat could be grown intensively or even continuously and could also be sown earlier in autumn.

Herbicides used for weed management in wheat fall under two categories: those applied prior to crop emergence (PRE) and after crop emergence (POST). Most commonly used PRE wheat herbicides in Europe are trifluralin, pendimethalin, isoproturon, and chlorotoluron, which are broad-spectrum herbicides with activity against both grass and broadleaf weeds. POST grass herbicides are clodinafop, fenoxaprop, diclofop, difenzoquat, and tralkoxydim while POST broadleaf herbicides include MCPA, mecoprop, metsulfuron, fluroxypyr, thifensulfuron, ioxynil, bromoxynil, amidosulfuron, and florasulam. Herbicides such as isoproturon, chlorotoluron , imazamethabenz, and diflufenican are also applied as POST and control both broadleaf and grass weeds. As a result of generic competition, the cost of isoproturon declined by 41% between 1995 and 2001 [28]. Isoproturon has been successfully used for the control of a wide spectrum of annual grasses and certain broadleaf weeds.

Weed control strategies for European winter wheat often require multiple herbicide applications or combinations of products to achieve satisfactory results. Additionally, herbicide resistance has developed in recent years further complicating the control of weeds in wheat [26].

Without control, weeds would lower wheat yields by 20-25% in Europe; with current herbicide use, the loss of wheat yields to weeds is estimated at 8% [25].

Cleavers is a common annual broadleaf weed of winter wheat. It is autumn germinating and favors high nitrogen rates and minimal tillage rather than plowing. Hence, Cleavers proliferated on farms where continuous autumn sowing of wheat with minimum tillage was adopted [32]. Control of cleavers with residual herbicides applied in the autumn increased wheat yield by 32% over the untreated control.

Autumn treatment with a residual herbicide often does not provide satisfactory season-long control of cleavers. Isoproturon tank-mixed with pendimethalin has provided the most satisfactory residual control of cleavers.

Weed species that emerge over a long period may not be adequately controlled by herbicides applied in the autumn and further treatment may be required in the following spring.

In organic wheat, mechanical weed control with inter-row hoeing has been experimented with; however, crop damage is a limiting factor with an average reduction in wheat yield of 11% [27].

Based on an average population of 2.5 million weed seedlings per acre (6.2 million/ha) and an average control efficacy of 95%, it is estimated that on the 98% of the E.U.'s wheat hectares treated with herbicides (16 million ha) that 97 trillion weed seedlings are killed annually.

In the U.S., approximately 38% of the nation's winter wheat acres receive herbicide treatment [7].

Table 3 delineates herbicide use in wheat in Germany, U.K., France and Italy in 1994.

A study of production practices in 1994 reported that in Germany 80% of the wheat acres were treated with herbicides while the percentage treated was above 90 in U.K. (95%), France (99%), and Italy (91%) [8]. The study determined the average herbicide treatment rates to be: (kg/ha) Germany (2.14), U.K. (1.72), France (1.70), and Italy (1.52) [8]. The primary herbicides used on wheat in each country are listed in Table 2. Growers in all four countries reported the resistance of black grass to isoproturon [8].

The weed control strategy in E.U. wheat is to apply a residual herbicide in the autumn followed in the spring with a postemergence spray [8]. Europe accounts for 35% of the worldwide sales of herbicides in wheat production [25].

France: The top wheat herbicides in France in 1994 were isoproturon, chlorotoluron , fluroxypyr, fenoxaprop, ioxynil, and metsulfuron (see Table 3). A commonly used herbicide program in wheat is an autumn application of isoproturon (1.0 kg ai/ha) plus diflufenican (0.125 kg/ha) followed by a spring application of clodinafop (0.03 kg/ha) + mecoprop (0.81 kg/ha), for a total AI of 1.96 kg/ha [19]. The cost of this program is estimated at €60/ha.

Germany: Based on a study conducted in 1994, isoproturon followed by fluroxypyr and MCPA were the most widely used wheat herbicides in Germany (see Table 3). However, use of pendimethalin and chlorotoluron increased by 1996 [14].

A widely used herbicide program by German wheat growers in recent years is a postemergence application of a premix of clodinafop plus florasulam plus carfentrazone in spring. About 0.06 kg of herbicide AI is applied at a cost of €72 per hectare [15].

Assuming half of Germany's wheat hectares receive 0.06 kg/ha of herbicide while the remaining half receives 2.14 kg/ha (the 1994 rate) implies an average use rate of 1.1 kg/ha.

Italy: An early POST application of diflufenican (0.15 kg ai/ha) + isoproturon (1.2 kg ai/ha) followed by a treatment for broadleaf weeds with fluroxypyr (0.18 kg/ha) or triasulfuron (0.007 kg/ha) is a widely used weed management approach in Italy [6]. On an average, about 1.45 kg of herbicide ingredients are applied per hectare in this approach at an average cost of €75/ha.

Another program used in Italy combines a pre-emergence application of trifluralin (0.8kg/ha) or pendimethalin (0.8kg/ha) plus linuron (0.4kg/ha) with a total cost of €30/ha, followed by a postemergence treatment with fluroxypur (0.18kg/ha) or triasulfuron (0.007 kg/ha) with an additional cost of €30/ha.

UK: A 2002 survey in the U.K. revealed that isoproturon was the most commonly used herbicide in wheat, with almost half the acreage being treated [21]. Table 4 shows the top herbicide active ingredients used in the U.K. in 2002. Wheat crops received an average of three herbicides. The average herbicide application rate in the U.K. in 2002 was 2.31 kg/ha [21]. The average wheat field in the U.K. received 2.31 kg/ha in herbicide application in 2002.

A widely used weed control program in U.K. wheat is an early POST application of flupyrsulfuron and a premix of clodinafop + trifluralin in autumn followed by a spring application of metsulfuron plus fluroxypyr [17]. The first application is aimed to control autumn-germinating blackgrass and some broad-leaf weeds such as ivy-leaved speedwell, which produces seeds before the spring applications and is consequently not effectively controlled. The second application is mostly for broadleaf weed control. A survey of U.K. wheat farms in 2002 indicated that the average cost of their herbicide program was £51.50/ha (€75/ha) [5]. Costs can approach £200/ha when resistant blackgrass is present [5].

<u>Weed resistance to herbicides</u>

Single applications of isoproturon or chlorotoluron used to result in very effective control of blackgrass [18].

Eight grass weeds (blackgrass, Italian ryegrass, rigid ryegrass, sterile oat, wild oat, wind bentgrass, hood canarygrass, and downy brome) and four broadleaf weeds (corn poppy, scentless chamomile, and common chickweed) have developed resistance to various herbicides used in wheat production in Europe. Major factors that led to the development of resistant grass weeds are continuous cereal plantings, use of no-till and direct seeding methods, early plantings, and over-reliance on certain herbicides [16].

In Italy, the recent appearance of weed resistance in durum wheat is particularly serious due to the absence of alternative herbicides for control of grassy weeds [29].

As a result of the occurrence of cross and multiple resistant populations, chemical control has become very difficult, as resistance against many herbicides may be present [31].

Research has focused on combinations of herbicides applied at different rates or timings for control of resistant populations. For example, while applications of isoproturon or fenoxaprop alone provided 70% control of blackgrass, their combination increased control to 95% [30]. The combination of isoproturon and trifluralin also increased the control efficacy to above 90% [30].

Grass weeds resistant to various herbicides belonging to the families arloxyphenoxypropionates (fops), cyclohexanediones (dims), ureas, sulfonylureas, and imidazolinones have been reported. Most significant of the reported cases is resistance in blackgrass to the most widely used urea herbicide isoproturon. Resistance development in grass weeds to 'fops' and 'dims' has also been a major concern in all of Europe as the numbers of detected cases have been increasing [5]. Though few broadleaf weeds have developed resistance to herbicides used in wheat, problems due to these weeds are insignificant in comparison to grass weeds, as these are the ones that compete the most with wheat and cause severe yield losses. The problem of weed resistance to the currently used herbicides is a major issue as resistant weeds exhibit resistance to multiple herbicides and alternative graminicides that provide effective control are not available.

Since its first confirmation in 1982, herbicide-resistant blackgrass increased steadily and infested about 34% of winter wheat acreage in U.K. by 1999. An earlier survey of 138 growers in U.K. indicated that roughly 14, 2, and 1% of wheat acreage was infested with resistant blackgrass, Italian ryegrass, and wild oats, respectively [16].

Over 750 farms in 30 counties throughout England have been confirmed as having resistant blackgrass populations. Many of these populations exhibit cross-resistance to a range of herbicides from differing chemical groups with differing modes of action [36].

Economically optimum sowing dates for wheat are prior to mid-October and any delay in sowing not only involves yield losses but also an increased risk of not being able to establish all the crop area in the autumn [18]. Many farmers have begun annual plowing for weed control and have delayed planting until mid-October [18].

Herbicide resistant blackgrass was first detected in England in 1982, resistant Italian ryegrass in 1990, and resistant wild oats in 1993 [37]. The total number of farms (750) where resistance has been detected represents about 4% of the estimated 20,000 cereal farms in the U.K. with a blackgrass problem (out of a total of 50,000 farms growing cereals). However, the majority of farms (greater than 90%) have not had any sample tested for resistance [37]. This figure (4%) is a minimum figure for the proportion of farms affected [37].

The presence of herbicide-resistant blackgrass and other weeds pose several problems besides yield and quality losses. For instance, the costs associated with herbicide-resistant blackgrass have been reported to be higher than the costs of herbicides used for its control as it restricts rotations, planting dates, and tillage methods. Since continuous winter plantings, use of no-till methods, and planting in the month of September were found to favor resistance development in blackgrass to herbicides, late planting in October into ploughed fields has been suggested. However, late plantings and abandonment of no-till practices increases wheat production costs in U.K. [4]. Furthermore, late plantings result in a yield penalty of at least 2% [18]. Yield losses ranging between 3 to 25% were predicted if crop husbandry practices are changed to prevent or stabilize the buildup of herbicide-resistant blackgrass populations [18]. Based on wheat yields of 8 tons per hectare, financial penalties from herbicide-resistant blackgrass were estimated to be €25 to €129 per hectare in U.K. [18].

The additional cost of herbicide use, plowing and yield loss resulting from the management of resistant blackgrass has been estimated to be as high as £143/ha [18].

<u>Herbicide-tolerant transgenic wheat</u>

Beginning in 1994, Monsanto conducted field trials in the U.S. with wheat cultivars that had been transformed through the insertion of a gene from a soil microorganism. This transformation makes it possible to spray wheat with glyphosate herbicide (Roundup) without crop injury. Glyphosate kills untransformed wheat plants by inhibiting the production of EPSP synthase –an enzyme necessary for production of key amino acids. The transformed plants have an additional gene that produces EPSP synthase that glyphosate does not inhibit. Thus the transformed wheat plants continue growing despite the application of glyphosate.

Research in North Dakota has shown that two applications of 12 oz/a of Roundup (0.75 lb ai/a) provided season-long control of wild oats, Canada thistle, and wild mustard [38][39]. Single glyphosate treatments applied early did not provide full season Canada thistle control while single late treatments did not remove early season weed competition. Research in Minnesota demonstrated that glyphosate applied alone provided 95 to 99% control of both grass and broadleaf weeds which was comparable to the control provided by other standard herbicides used in wheat [40]. No injury to the transgenic wheat has been observed in any of the field experiments [41].

A frequently mentioned benefit of Roundup Ready wheat is that growers will be able to control a broad spectrum of weeds with a single active ingredient in comparison to the 2-3 active ingredient applications, which are common at this time [42].

The potential impact in the U.S. of adopting glyphosate-tolerant wheat is an increase in grower income of $12/A [43].

No company is currently undertaking field trial work on herbicide tolerant wheat in the E.U.

Impacts of transgenic herbicide-tolerant wheat

Two major potential impacts of transgenic herbicide-tolerant wheat would be effective control of all the weed species including herbicide-resistant weeds with only one chemical rather than a battery of herbicides and reduction in weed control costs.

Experiments with glufosinate in the U.K. indicate that it provides 100% control of blackgrass populations resistant to other herbicide classes [30]. Quizalofop provided 17% control of the resistant blackgrass in this experiment.

The introduction of herbicide tolerant wheat crops should improve control of grass weeds notably blackgrass which has become resistant to selective herbicides [33].

A recent study estimated that herbicide tolerant wheat would likely be planted on 20% of the E.U.'s hectares due to economic benefits of improved weed control with higher yields and/or lower weed control costs [13].

The substitution of two glyphosate applications, totaling 1.0 lb ai/a (1.12 kg/ha), for the current herbicides used in wheat would lower herbicide use by 32% (see Table 5).

It is assumed that the cost of a glyphosate-tolerant program would be approximately €30/ha, which represents an average reduction of 47% from current costs (see Table 6).

It is assumed that the biotech varieties would be planted on 20% of the wheat hectares in the E.U. implying an overall reduction in herbicide use of 1.5 million kg and an annual overall saving of €90 million/yr.

It is assumed that wheat yields would be unaffected by the substitution of glyphosate for the current herbicides used in European wheat.

Table 1: Wheat Productivity in Various Countries in 2002	
	Wheat yield (kg/ha)
China	3,780
E.U.-15	5,744
India	2,728
U.S.	2,373
U.S.S.R.	2,442

Source: FAO

Table 2a: Wheat Production			
	Area (000 HA)	***Production (billion kg)***	***Value (€ billion)***
France	4769	31.6	3.6
Germany	2897	22.8	2.5
Italy	2289	6.4	0.9
Spain	2203	4.9	0.7
U.K.	1636	11.6	1.5
Total E.U.	16795	91.8	11.1
U.S.	19461	53.4	5.4

Source: [22] [23] [24]

Table 2b: Wheat Production			
	Area (000 A)	***Production (billion Lbs)***	***Value ($ billion)***
France	11923	70.0	3.6
Germany	7243	51.2	2.5
Italy	5723	14.1	0.9
Spain	5508	10.8	0.7
U.K.	4090	25.5	1.5
Total E.U.	41988	202.0	11.1
U.S.	48653	117.4	5.4

Dollars and Euros assumed equivalent.

Table 3: Herbicide Use in Wheat (1994)		
Germany	***% Crop Treated***	***G AI/HA***
Isoproturon	89	976
Fluroxypyr	69	102
MCPA	32	668
MCPP-P	27	620
Bifenox	22	313
2,4-DP	12	705
MCPP	12	663
Metsulfuron	11	3
Diflufenican	8	59
U.K.	***% Crop Treated***	***G AI/HA***
Metsulfuron	58	4
Fluroxypyr	53	166
Fenoxaprop	37	112
Thifensulfuron	16	35
Glyphosate	14	865
MCPA	14	975
Ioxynil	13	115
Bromoxynil	13	131
Fenoxaprop	7	35
Isoproturon	34	2177
France	***% Crop Treated***	***G AI/HA***
Isoproturon	31	1,125
Chlorotoluron	25	1,564
Fluroxypyr	24	158
Fenoxaprop	24	50
Ioxynil	24	170
Metsulfuron	21	4
Bifenox	16	472
MCPA	15	639
Diflufenican	14	138
MCPP	13	658
MCPP-P	12	438
Cloquintocet	12	11
Clodinafop	12	45
Chlorsulfuron	11	16

Italy	***% Crop Treated***	***G AI/HA***
MCPA	24	619
MCPP	23	783
Ioxynil	23	246
Tribenuron	22	12
Methabenz – Thiazuron	18	2,002
Diflufenican	17	113
Trifluralin	16	833
Linuron	15	431
Isoproturon	13	1,235
Pendimethalin	13	799
Bromoxynil	12	274

Source: [8]

Table 4: Herbicide Use in Wheat, U.K. (2002)		
	% Area Treated	***Herbicide Use Rate (kg ai/ha)***
Isoproturon	45	1.31
Fluroxypyr	31	0.11
Glyphosate	27	0.73
Flupyrsulfuron	26	0.01
Diflufenican/Isoproturon	23	0.62

Source [21]

Table 5: Potential Impact of Glyphosate-Tolerant Wheat on Herbicide Use in Europe

	Area (000 ha)	*Herbicide use rate (kg ai/ha)*		*Change in herbicide use (kg ai/ha)*	*Total herbicide use (million kg)*		*Change in herbicide use (million kg)*
		Current	*Biotech*		*Current*	*Biotech*	
France	4769	1.96	1.12	-0.84	9347	5341	-4006
Germany	2897	1.10	1.12	+0.02	3187	3245	+58
Italy	2289	1.45	1.12	-0.33	3319	2564	-755
Spain	2203	1.45	1.12	-0.33	3194	2467	-727
U.K.	1636	2.31	1.12	-1.19	3779	1832	-1947
Total	13794				22826	15449	-7377

Source: [6] [8] [15] [19] [21]

It is assumed that two applications of glyphosate at 0.56 kg ai/ha each would replace conventional herbicide programs in all countries.

100% adoption assumed.

Spain is assumed identical to Italy.

Table 6: Potential Impact of Glyphosate-Tolerant Wheat on Weed Control Costs					
	Area (000 ha)	***Weed Control Costs (€/ha)***		***Savings (€/ha)***	***Total Savings (€ million/yr)***
		Conventional	*Biotech*		
France	4769	60	30	30	143
Germany	2897	72	30	42	122
Italy	2289	75	30	45	10
Spain	2203	75	30	45	99
U.K.	1636	75	30	45	74
Total	13794				448

Source: [5] [6] [15] [19]
Spain is assumed identical to Italy.
Assumptions made for weed control calculations with glyphosate-tolerant wheat: Cost of glyphosate = €18/kg; Technology fee = €10/ha. It is assumed that two POST applications of glyphosate at 0.56 kg ai/ha each would replace conventional herbicides.

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