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Impact of Imazamox and Imazapyr Carryover on Wheat, Barley, and Oat

Julio A. Scursoni, Jorgelina C. Montoya, Mario R. Vigna, Ramón Gigón, Carolina Istilart, Juan P. Renzi Pugni, Ricardo López, and Carolina Porfiri*

Imazapyr and imazamox are frequently applied postemergence to control grass and broadleaf weeds in imidazolinone-resistant sunflower in Argentina. Herbicide carryover to rotational crops represents a disadvantage of these herbicides, particularly in regions with low rainfall during the months prior to rotational crop sowing. Between 2009 and 2012, field and greenhouse studies were conducted on four important sunflower-cropped areas of Argentina. The objective was to quantify the effects of imazapyr alone and imazamox plus imazapyr applied in sunflower crops on the subsequent establishment, growth, and yield of barley, oat, and wheat. In all field experiments, imazapyr alone and imazamox plus imazapyr were applied at recommended rates (80 g ha^{-1} and 66 plus 30 g ha^{-1}, respectively), and also, in some experiments, at double the recommended rates. Soil bioassays were also conducted in the greenhouse to study the effect of these herbicides on barley, oat, and wheat seedlings. The mixture of imazamox plus imazapyr was safer for rotational crops than imazapyr applied alone, because of the reduced rate of imazapyr in the mixture treatments. Barley was more sensitive to imidazolinones, particularly imazapyr, than the other winter cereals. Imazapyr at double rate (160 g ha^{-1}) reduced barley yield by 45% when seeds were sown 165 d after herbicide application and with 240 mm rainfall after herbicide application.

Nomenclature: Imazamox; imazapyr; barley, *Hordeum vulgare* L.; oat, *Avena sativa* L.; sunflower, *Helianthus annuus* L.; wheat, *Triticum aestivum* L.

Key words: Imidazolinone herbicides; carryover.

Sunflower is one of the four most important annual crops in the world grown primarily for edible oil. Argentina is the fourth largest producer of oilseed sunflowers globally behind Ukraine, Russia, and the European Union, and one of the largest sunflower oil exporters (ASAGIR 2014). The average area sown to sunflower in Argentina during the years 2014–17 was around 1,700,000 ha. The most important area is Buenos Aires Province, which represents almost 50% of the entire Argentine production (Ministerio de Agricultura de Argentina 2013).

Many studies have documented the susceptibility of sunflower to yield loss from weed interference, particularly at early stages of the crop. Durgan et al. (1990) reported that kochia [*Kochia scoparia* (L.) Schrad.], at a population density of six kochia plants per meter of row, caused yield losses of 20% to 36%, depending on water availability. Moreover, when kochia plants emerged jointly with sunflower, yield was reduced up to 76%. Thus, sunflower growers should be proactive against weeds, particularly when the plants emerge at about the same time as the sunflower (Lewis and Gulden 2014). In Argentina, Bedmar et al. (1983) found that a 20-d weed-free period following sunflower emergence was required to prevent significant yield losses attributable to weed interference. However Montoya et al. (2008) reported that a weed-free period of 30 d was needed to prevent yield reduction.

Flurochloridone, diflufenican, sulfentrazone, flumioxazin, acetochlor, and metolachlor are frequently applied PRE in Argentina to control broadleaf and grass weeds in sunflower (Istilart 2002; Montoya et al. 2008). However, the efficacy of these herbicides is

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* First author: Associate Professor, Plant Production Department, Facultad de Agronomía, Universidad de Buenos Aires, Avenida San Martín 4453 (1417), Buenos Aires, Argentina; Second and eighth authors: Weed Researchers, EEA INTA Anguil, Ruta Nacional Nº 5 Km 580 (6326), Anguil, La Pampa, Argentina; Third and seventh authors: Weed Researchers, EEA INTA Bordenave, Ruta Provincial 76 Km 36.5 (8187), Bordenave, Provincia de Buenos Aires, Argentina; Fourth and fifth authors: Weed Researchers, EEA INTA Barrow Ruta 3 Km 488 (7500), Tres Arroyos, Argentina; Sixth author: Weed Researcher, EEA INTA Hilario Ascasubi-CERBAS, Ruta 3 Km 794 (8142), Hilario Ascasubi, Argentina. Corresponding author's E-mail: scursoni@agro.uba.ar

strongly dependent on rainfall or irrigation. Sunflower producers have few herbicide options, such as benazolin or aclonifen, for early POST broadleaf weed control in sunflower in Argentina (Montoya 2016). Therefore, the introduction of imidazolinone (IMI)-resistant (IR) sunflowers in Argentina and the concomitant use of IMI herbicides represented a major technological advance for weed control. In IR sunflower, using a PRE herbicide can delay the critical time for weed removal (CTWR) by an additional 6 to 12 d compared to sunflower grown without a PRE herbicide application. The CTWR without PRE herbicide treatment ranged from 14 to 26 d after emergence, corresponding to the V3 (three leaves) to V4 stages. However, a PRE herbicide treatment increased the CTWR 25 to 37 d after emergence, corresponding to the V6 to V8 stages (Knezevic et al. 2002; Knezevic et al. 2013). This practice increases weed control efficacy when using IMIs, because weeds often emerge later than without PRE application, and thus, POST IMI application will typically target smaller weeds than without PRE herbicides. This timing is relevant, because the success of this technology depends on the growth stage of the weeds at the time of herbicide application (Fedoruk and Shirtliffe 2011). In addition, there is also a restriction on sunflower growth stage (one leaf pair to four leaf pairs). Additionally, the residual control offered through PRE herbicide application reduces or prevents weed competition until after the sunflower seed number is already set (between floral initiation, 30 d prior to anthesis, up until 20 d after 50% first anthesis) (Cantagallo et al. 1997).

The IMI herbicides inhibit acetolactate synthase and are used extensively for broad-spectrum weed control in soybeans [*Glycine max* (L.) Merr.] and other selected legumes, as well as in IR crops. Microbial degradation is the main route of dissipation of these herbicides in the soil; thus, IMI herbicides applied to the soil are affected by soil type, pH, organic matter, moisture, and temperature (Loux and Reese 1993; Kraemer et al. 2009). In Argentina, application of herbicides such as imazapyr and imazamox to IR sunflower is the chief technology used to control weeds. Growers commonly apply herbicides when the crop is at the V4 stage, when broadleaf weeds are at the two- to four-leaf stage, or when grasses have three leaves. Persistence of the IMI herbicides applied to IR sunflower could cause phytotoxicity on certain crops included in the rotation. This persistence is related largely to the amount of rain between herbicide application and planting of the next crop (Istilart 2005). In the south and west of Buenos Aires Province, where this technology has been widely adopted, it is a concern for farmers that herbicide carryover may affect the establishment and growth of winter cereals or green manures sown during autumn and winter following sunflower harvest.

Imazapyr was released in Argentina in 2003 to be applied early POST at 80 g ai ha^{-1} in IR sunflowers. The main advantages of this technology are the broad-spectrum weed control and residual effect. However, the potential for imazapyr carryover and the impact on crop rotation options have not been well described (Montoya et al. 2008). Moreover, reports were published indicating residual carryover damage to alfalfa (*Medicago sativa* L.), oat, rye (*Secale cereale* L.), sugar beet (*Beta vulgaris* subsp. *vulgaris*), pea (*Pisum sativum* L.), melon (*Cucumis melo*.), corn (*Zea mays* subsp. *mays*), pepper (*Capsicum annuum* L.), and tomato (*Solanum lycopersicum* L.) when they were planted in rotation with crops where IMI herbicides had been applied (Alister and Kogan 2005). Recently, a new herbicide formulation containing a mixture of imazamox and imazapyr (33 and 15 g ai L^{-1}, respectively) has become available in Argentina with the aim of reducing potential carryover to cereal crops. Accordingly, the objective of this study was to evaluate the carryover potential of IMI herbicides on the establishment, growth, and yield of barley, wheat, and oat planted in rotation with IR sunflowers. In addition, we studied the effects of these herbicides on germination and seedling growth of these crops by means of controlled bioassay experiments.

Materials and Methods

Two field experiments were established at the Agricultural Experimental Station (EEA) INTA Anguil, west Buenos Aires Province (36°50′ S, 64° W) and two at EEA INTA Bordenave, southwest Buenos Aires Province (37°10′ S, 63° W) in 2009–2010 and 2011–2012. Another experiment was conducted at EEA INTA Hilario Ascasubi, south Buenos Aires Province (39°20′ S, 62°30′ W) in 2011–2012. In addition, soil bioassay experiments were conducted at Bordenave during 2009–2010 and 2011–2012 and at Tres Arroyos during 2009–2010.

Historical average annual rainfall in Anguil, Bordenave, and Tres Arroyos is 759, 677, and 758 mm, respectively; annual rainfall in Hilario Ascasubi is lower than in other areas (491.9 mm), but crops are often supplemented with irrigation (Table 1). In Anguil, typical soils are sandy loam Haplustolls, with 2.5% organic matter (OM) and pH 6.4. Soils in Bordenave are also loam Haplustolls, with pH 6.4 and 3.3% OM, whereas soils in Tres Arroyos are sandy-clay loam Argiudolls containing 3.8% OM with pH 6.3. In Hilario Ascasubi, soils are a sandy loam Haplustolls but with less OM (1.2%) and higher pH (7.5) than in the other areas.

At Anguil in 2009–2010 and 2011–2012, treatments were arranged in a split-plot design with herbicide treatment as the whole plot and the crops sown after the sunflower harvest as split-plots. Herbicide treatments in sunflower (Table 2) were applied when broadleaf weeds were at the two- to four-leaf stage on December 12, 2009 (30 d after sunflower emergence). Barley, oat, and wheat were sown at recommended population densities (300 plants m^{-2}) 90 days after the sunflower harvest on June 23. In 2011–2012, herbicide treatments were applied to sunflower on December 1 (26 d after sunflower emergence), and barley, wheat, and oat were sown at 300 plants m^{-2} on June 19, 100 d after sunflower harvest. Non-IMI control plots were treated with PRE herbicides (Table 2). In addition, propaquizafop was applied post emergence. The effect of IMI treatments was compared to these plots.

At Bordenave in the 2009–2010 trial, treatments in each crop were arranged in a split-plot design, with herbicide treatment as the whole plots and sowing date as split-plots. Herbicide treatments (Table 2) were applied on January 15, 2010 (32 d after sunflower emergence). Barley, oat, and wheat were sown at recommended densities (between 180 and 220 plants m^{-2}) on April 10 and at 230 to 250 plants m^{-2} on July 1. In 2011–2012, the trial was arranged as a randomized complete block, and herbicide treatments (Table 2) were applied on October 15, December 1, January 15, and March 1 (240, 195, 150, and 105 d before cereal crop sowing). In non-IMI control plots, weeds were controlled by means of PRE application of sulfentrazone plus *S*-metolachlor. Barley and wheat were sown at recommended densities (250 plants m^{-2}) on June 15.

At Hilario Ascasubi in 2011–2012, treatments were arranged in a split-plot design with timing of

Table 1. Monthly rainfall (mm) at experimental stations during 2009, 2010, 2011, and 2012.

Month[a]	Anguil				Tres Arroyos				Bordenave				Hilario Ascasubi			
	2009	2010	2011	2012	2009	2010	2011	2012	2009	2010	2011	2012	2009	2010	2011	2012
	Rainfall (mm)															
Jan	8	95	218	85	38	51	126	53	8	41	185	24	5	12	166	59
Feb	81	210	15	127	28	259	36	85	23	109	33	104	24	152	14	52
Mar	65	383	101	93	131	80	50	112	66	57	88	105	45	75	73	95
Apr	9	14	140	76	26	39	43	24	0	3	57	28	13	24	47	15
May	24	7	18	14	42	50	12	104	19	11	23	60	9	23	13	7
Jun	0	10	8	3	56	48	40	29	0	19	19	3	4	25	6	17
Jul	7	10	29	0	38	92	34	6	24	15	14	0	46	7	1	0
Aug	0	0	11	96	4	6	16	193	3	2	16	98	5	0	11	36
Sep	72	80	2	29	36	51	20	16	50	100	1	37	26	36	6	17
Oct	21	76	68	192	46	71	28	50	9	51	98	122	6	67	55	15
Nov	93	23	132	101	74	139	190	131	72	57	196	77	38	20	77	26
Dec	80	18	39	152	61	32	93	208	194	8	14	148	65	0	39	87
Total	460	926	781	968	580	918	688	1011	468	473	744	806	286	441	509	426

[a] Abbreviations: Jan, January; Feb, February; Mar, March; Apr, April; Jun, June; Jul, July; Aug, August; Sep, September; Oct, October; Nov, November; Dec, December.

Table 2. Herbicide treatments applied and crops sown in field experiments conducted in Anguil, Bordenave, and Hilario Ascasubi.

Herbicide	Rate	Anguil		Bordenave		Hilario Ascasubi
		2009–2010	2011–2012	2009–2010	2011–2012	2011–2012
	g ha^{-1}					
Imazapyr	80	B O W[a]	B O W	–[b]	B W	W
Imazapyr	160	B O W	B O W	B O W	–	–
Imazapyr	30	B O W	B O W	B O W	B W	W
+ imazamox	66					
Imazapyr	60	B O W	B O W	B O W	–	–
+ imazamox	132					
Sulfentrazone	100	B O W	B O W	B O W	B W	–
+ *S*-metolachlor	960	–	–	–	–	W
Imazethapyr	80					

[a] Abbreviations: B, barley; O, oat; W, wheat.

[b] Dash (–) indicates that treatment was not included at location/year.

herbicide application as the main plot and herbicides treatment as the split-plot. Herbicide treatments (Table 2), were applied on four dates (September 21, November 4, January 12, and March 5) 268 to 104 days before the sowing. Wheat was sown at recommended population density (250 plants m^{-2}) on June 19.

Plot size in Anguil was 10 by 10 m; in Bordenave and Hilario Ascubi, plot size was 5 by 10 m. Four replications of each treatment were established in each experiment at all locations. All the cereal crops were fertilized with 55 kg P ha^{-1} and 76 kg N ha^{-1} at sowing. Weeds in cereal crops were controlled with metsulfuron-methyl plus dicamba applied before the beginning of the crop tillering or 2,4-D plus dicamba from the beginning to the end of tillering. Herbicides were applied with a tractor-mounted, compressed-air sprayer calibrated to deliver 100 L ha^{-1} at 294 kPa using flat-fan nozzles.

Wheat, barley, and oat seedlings were counted 30 to 40 d after emergence in three 1-m^2 quadrats within each plot. At Anguil and Bordenave, crops were harvested at maturity from 0.5-m^2 quadrats in each plot, and dry biomass was measured after drying for 48 h at 60 C. Grain yield was also assessed from 5.75-m^2 quadrats within each plot. At Hilario Ascasubi, each plot was harvested by combine, and grain yield was measured.

Soil Bioassay Experiments. Soil experiments were conducted at Bordenave during 2009–2010 and 2011–2012 and at Tres Arroyos during 2009–2010. Soil samples were extracted from field-treated plots at depths of 0–10 cm and 10–20 cm to determine the impact of herbicide carryover on seedling establishment and growth. At Tres Arroyos, herbicide treatments were the same as those described at Anguil (Table 2), applied on January 15, 2010. Control plots were treated with fluorochloridone (375 g ai ha^{-1}) and acetochlor (900 g ai ha^{-1}).

At Bordenave, soil samples were taken at 120 and 180 d after application (DAA) during 2009–2010, and bioassays were conducted with barley, oat, and wheat. During 2011–2012, samples were taken at 105, 150, 195, and 240 DAA, and bioassays were conducted with barley and rapeseed (*Brassica napus* L.). At Tres Arroyos, oat and wheat bioassays were conducted using soil samples taken 230 DAA.

Soil samples collected from each plot were sifted through a 1-mm-mesh sieve stored in a freezer for a month; after that 700 g of soil was placed in each pot. Three replications were prepared for each treatment, with seeds of wheat, oat, barley, or rapeseed sown in each pot. Pots were placed in a growth chamber under controlled conditions: 12 h of light and alternating temperatures of 18 C and 25 C (night/day). The pots were watered so as to maintain soil at field capacity, using the same amount of water for each pot. When wheat, barley, or oat seedlings reached Zadoks stage 12 (Zadoks et al. 1974), number of emerged seedlings, root length and seedling height (cm), and shoot and root dry weights (g) were assessed. For rapeseed, seedlings were counted when they reached the two-leaf growth stage.

Statistical analyses were carried out with the InfoStat statistical software (Facultad de Ciencias Agropecuarias, UNC, Argentina). Because experimental designs and treatments were not identical for the different experiments because different logistic resources were available at each site, analyses were conducted separately for each experiment, location, and year. Thus, location and year were not considered as classification variables in the analyses. For all bioassays, data were analyzed separately for each crop, and the ANOVA was carried out as a randomized complete block design regarding each date of soil sampling × herbicide treatment. All data were subjected to ANOVA with statistical models suited to the experimental design of each experiment, after which, when the F-test indicated effects were significant ($P < 0.05$), means were separated using Fisher's protected LSD ($P < 0.05$).

Results and Discussion

2009–2010 Field Experiments. *Bordenave.* The number of emerged seedlings was not affected by herbicide treatment ($P > 0.05$) in any crop (data not shown). Imazapyr applied at 160 g ha^{-1} reduced barley and wheat biomass and yield when crops were sown in April, but herbicide treatments did not affect oat biomass or yield. When crops were sown in July, imazapyr also reduced barley yield (Table 3). Rainfall between herbicide application and cereal crop sowing, around 210 mm and 240 mm for the April and July sowing, respectively, was not sufficient to reduce imazapyr levels, through either degradation or dissipation, to amounts that were safe for planting barley and wheat. Although 165 d passed between herbicide application and the July sowing, imazapyr at double rate was persistent enough to reduce barley yield. The effects of the double dose represent the damage that can be generated when overlaps occur in the application strips.

Anguil. Similarly to Bordenave, there was no effect of herbicide on barley, oat, or wheat establishment. Rainfall from December to June was around 700 mm, and crop grain yield and total biomass were not affected ($P > 0.05$) by herbicide treatment, nor was there a significant interaction between herbicide treatment and crop (Table 4). This result, contrasted with Bordenave, shows the importance of the rainfall regime on microbial degradation of these herbicides to reduce carryover on crops in the rotation. Cantwell et al. (1989) concluded that microbial degradation of the IMI herbicides was a function of the amount of herbicide in the soil solution.

2011–2012 Field Experiments. *Bordenave.* The number of seedlings was not affected by herbicide treatment ($P > 0.05$) in any crop (data not shown). Wheat biomass and grain yield were not affected by

Table 3. Barley and wheat mature biomass and yield at two sowing times with different herbicide treatments at Bordenave (2009–2010).[a]

	Planting month			
	April 2009	July 2009	April 2009	July 2009
	Biomass (g m^{-2})		Yield (g m^{-2})	
Barley				
Non-IMI control[b]	725	654	233	211
Imazapyr 160 g ha^{-1}	530	615	93	96
Imazapyr 30 g ha^{-1} + imazamox 66 g ha^{-1}	775	759	252	228
Imazapyr 60 g ha^{-1} + imazamox 132 g ha^{-1}	649	824	179	190
LSD ($P < 0.05$)[c]	191	180	72	56
Wheat				
Non-IMI control	383	276	147	102
Imazapyr 160 g ha^{-1}	228	232	81	84
Imazapyr 30 g ha^{-1} + imazamox 66 g ha^{-1}	485	196	185	82
Imazapyr 60 g ha^{-1} + imazamox 132 g ha^{-1}	411	265	137	104
LSD ($P < 0.05$)	93	NS[d]	41	NS

[a] Herbicide treatments were applied to sunflower on January 15, 2010. Barley and wheat were sown on April 10 and on July 1, 2010, and biomass and yield were measured on December 5 and 20, 2010, respectively.

[b] Herbicide treatment: Sulfentrazone (100 g ha^{-1}) + *S*-metolachlor (960 g ha^{-1}). Abbreviation: IMI, imidazolinone.

[c] Data were analyzed by ANOVA regarding the split-plot design. Means were separated using Fisher's protected LSD ($P < 0.05$).

[d] Non-significant (NS) differences ($P > 0.05$).

Table 4. Barley, wheat, and oat mature biomass and yield response to carryover of herbicide treatments applied in a previous sunflower crop in Anguil.

	2009–2010[a]		2011–2012[b]	
	Biomass (g m^{-2})	Yield (g m^{-2})	Biomass (g m^{-2})	Yield (g m^{-2})
Barley				
Non-IMI control[c]	716	190	977	313
Imazapyr 80 g ha^{-1}	802	194	965	303
Imazapyr 160 g ha^{-1}	711	196	1027	327
Imazapyr 30 g ha^{-1} + imazamox 66 g ha^{-1}	672	183	896	329
Imazapyr 60 g ha^{-1} + imazamox 132 g ha^{-1}	604	155	965	315
Oat				
Non IMI Control	690	161	882	134
Imazapyr 80 g ha^{-1}	778	139	1022	150
Imazapyr 160 g ha^{-1}	729	185	912	174
Imazapyr 30 g ha^{-1} + imazamox 66 g ha^{-1}	804	167	707	157
Imazapyr 60 g ha^{-1} + imazamox 132 g ha^{-1}	775	141	715	156
Wheat				
Control	831	134	1036	250
Imazapyr 80 g ha^{-1}	903	155	869	227
Imazapyr 160 g ha^{-1}	812	189	1156	264
Imazapyr 30 g ha^{-1} + imazamox 66 g ha^{-1}	807	188	983	247
Imazapyr 60 g ha^{-1} + imazamox 132 g ha^{-1}	779	162	869	265
Herbicide treatment	$P = 0.59$	$P = 0.11$	$P = 0.34$	$P = 0.84$
LSD ($P < 0.05$)[d]	NS[e]	NS	NS	NS
Crop	$P = 0.07$	$P = 0.09$	$P = 0.178$	$P < 0.0001$
LSD ($P < 0.05$)	NS	NS	NS	42.7
Herbicide × Crop	$P = 0.94$	$P = 0.62$	$P = 0.76$	$P = 0.99$
LSD ($P < 0.05$)	NS[e]	NS	NS	NS

[a] Herbicide treatments were applied to sunflower on December 12, 2009. Small-grain crops were sown on June 23, 2010, and biomass and yield were measured on December 10, 2010.

[b] Herbicide treatments were applied to sunflower on December 1, 2011. Small-grain crops were sown on June 19, 2012, and biomass and yield were measured on December 12, 2012.

[c] Herbicide treatment: PRE: Sulfentrazone (100 g ha^{-1}) + *S*-metolachlor (960 g ha^{-1}), and POST: propaquizafop (150 cm^3 ha^{-1}). Abbreviation: IMI, imidazolinone.

[d] Data were analyzed by ANOVA regarding the split-plot design. Means were separated using Fisher's Protected LSD ($P < 0.05$).

[e] Non-significant (NS) differences ($P > 0.05$).

any herbicide treatment at the rates tested, regardless of application timing. Rainfall was at least 320 mm between treatment application and sowing. However, barley yield was reduced when sown 105 d after imazapyr (80 g ha^{-1}) application with 187 mm rainfall between application and sowing (data not shown). Thus, it is possible to conclude that 300 mm rainfall during 150 d from the application are sufficient to allow for sowing winter cereals into fields that were previously treated with the IMI herbicides imazapyr and imazamox in a sunflower crop. This result is in agreement with Ball et al. (2003), who also found that barley was more sensitive than wheat to imazamox and that yield of spring wheat grown after pea treated with imazamox was reduced only with a rate of 90 g ha^{-1}, but spring barley was reduced by 45 g ha^{-1}. Moreover, imazamox application at 36 g ha^{-1} injured barley and canola grown 1 year after imazamox treatment at locations in Oregon with low rainfall (400 mm) and low soil pH, but injury was not observed at locations with higher rainfall.

Anguil. Even though rainfall between January and June was 217 mm less than during the 2009–2010

Table 5. Wheat yield as influenced by timing of imazethapyr and imazapyr application in Hilario Ascasubi.

	No. of days from treatments to sowing[a]			
	268	222	154	104
	Yield (kg ha^{-1})			
Imazethapyr 100 g ha^{-1}	2,158	3,055	2,478	1,912
Imazapyr 80 g ha^{-1}	2,504	2,608	2,139	2,666
Imazapyr + imazamox 30 + 66 g ha^{-1}	2,432	3,341	1,858	2,378
Non-IMI control[b]	2,691	3,425	4,211	3,567
LSD ($P < 0.05$)[c]	511			

[a] Herbicides were applied on September 21, 2011, November 4, 2011, January 12, 2012, and March 5, 2012, and wheat was sown on June 19, 2012.

[b] Herbicide treatment: Sulfentrazone (100 g ha^{-1}) + *S*-metolachlor (960 g ha^{-1}). Abbreviation: IMI, imidazolinone.

[c] Data were analyzed by ANOVA regarding the split-plot design. Means were separated using Fisher's protected LSD ($P < 0.05$).

growing season (Table 1), still no effect of herbicide treatments or interactions of herbicide and crop on biomass and grain yield were apparent ($P > 0.05$) (Table 4). Total rainfall between January and June was 501 mm.

Hilario Ascasubi. Herbicide treatments reduced yield when applied at either 104 or 154 d before sowing (Table 5). Further, imazapyr reduced wheat yield when applied 222 d before sowing, showing greater carryover than in Anguil and Bordenave. However, herbicide treatments applied 265 d before the sowing did not reduce grain yields. The lower OM, lower rainfall, and higher pH at Hilario Ascasubi explain the greater herbicide carryover when compared with Bordenave and Anguil.

The ionization coefficients (pKa) of the carboxylic group of imazethapyr, imazapyr, and imazamox are 3.9, 3.6, and 3.3, respectively (PPDB, 2016). For weak acids such as these herbicides, when the pH of the soil solution is equal to the pKa, the molecules are 50% associated neutral (COOH) and 50% dissociated or anionic (COO^{-}) (Kraemer et al. 2009). If the pH is higher than the pKa, dissociated molecules predominate, and if pH is below the pKa, neutral molecules predominate. At soil pH values of 5 or greater, these compounds primarily exist as negative ions and are weakly sorbed (Mangels 1991). In contrast, adsorption increases with high OM content in the soil and when pH values decrease (Gianelli et al. 2011). Although these herbicides differ only slightly in chemical structure, they have widely different potential for carryover injury to subsequent crops (Bhalla et al. 1991). Imazamox has the shortest rotational restrictions, because it dissipates relatively rapidly compared to other IMI herbicides and thus allows the planting of crops after a shorter interval (Aichele and Penner 2005; Shaner and Hornford 2005). At pH 7, the half-life for imazamox was 1.4 wk; for imazethapyr it was 16 wk (Aichele and Penner 2005). In addition, among the IMI herbicides, metabolism followed the sequence imazamox > imazethapyr > imazaquin, with metabolism greater at pH 7 than pH 5 (Aichele and Penner 2005). Imazapyr is not easily degraded in soil and can be very persistent, depending on the type of soil, environmental conditions, and the rate of application (Mangels 1991). The persistence of imazapyr in the soil is mainly affected by microbial degradation. Soil half-life (time required for 50% of the pesticide originally applied to degrade into other products) ranged between 25 and 142 d, being shorter in sandy soil and with elevated temperatures and rainfall (Tu et al. 2004, cited in Gianelli et al. 2011).

In addition, fields treated with IMI herbicides such as imazapic and imazapyr require rainfall >300 mm for the degradation of these herbicides to allow planting oats, wheat, and malting barley without risk of phytotoxicity (Istilart 2005). Our results are in agreement with those of Istilart (2005), whose recommendations for use of imazamox plus imazapyr in Argentina include a crop rotation restriction of at least 3 mo for barley, wheat, and rye, and 5 mo for oat, rice, and corn. However, our results showed barley to be more sensitive than oat. These results are in agreement with Alister and Kogan (2005), who reported barley to be more sensitive than oat after application of the IMI herbicides imazapyr plus imazapic.

IMI herbicide adsorption to colloids increases as the soil dries, rendering them unavailable for microbial degradation. Among the factors that affect microbial activity are moisture, temperature, pH, oxygen, and nutrient supply. Usually a warm, well-aerated, fertile soil with a neutral pH is the most favorable for microbial growth and therefore for herbicide degradation. For IMI herbicides, temperature and moisture are more important factors than soil pH to increase microbial activity.

Table 6. Shoot height and root length of rape and barley[a] grown in soil samples in 2011–2012 at Bordenave.

Herbicide	Rate	Rapeseed Shoot height	Rapeseed Root length	Barley Shoot height	Barley Root length
	g ha^{-1}	cm			
105 DAA					
Imazapyr	80	44	57	166	140
Imazapyr + imazamox	15 + 33	45	47	159	135
150 DAA					
Imazapyr	80	49	70	172	151
Imazapyr + imazamox	15 + 33	56	93	168	173
Non-IMI control[b]		59	91	175	201
LSD ($P < 0.05$)[c]		9	34	16	39

[a] Samples were taken from a depth of 0 to 10 cm 150 and 105 DAA (days after application).

[b] Herbicide treatment: Sulfentrazone (100 g ha^{-1})+ *S*-metolachlor (960 g ha^{-1}). Abbreviation: IMI, imidazolinone.

[c] Data were analyzed by ANOVA regarding the split-plot design. Means were separated using Fisher's protected LSD ($P < 0.05$).

Bioassay Studies. For soil collected at Bordenave during the 2009–2010 season, soil bioassays did not show differences ($P >$ 0.05) between herbicide treatments and sample depth regardless of crop planted (data not shown). For soil collected at Bordenave during 2011–2012, root length and seedling height for rapeseed and barley were less than those of control plots for soil samples taken from 0 to 10 cm depth 105 DAA (Table 6), but no differences were found when samples were taken from 10 to 20 cm depth. Samples taken 150 DAA showed effect on rapeseed shoot height and root length of barley. Interestingly, growth of rapeseed was also reduced in samples taken 240 DAA (data not shown). For soil collected from Tres Arroyos, there was no significant effect ($P >$ 0.05) on oat seedlings and root dry biomass, but all the treatments reduced wheat seedling and root dry biomass (Table 7). Gianelli et al. (2011) reported that imazapyr applied at 80 and 160 g ha^{-1} reduced wheat seedling dry weight 25% and 53% compared with the control, respectively, at 138 DAA. It was necessary that 5 to 9 mo pass and for 500 to 730 mm of rain to fall after application of imazapyr to IR sunflower before wheat could be planted without risk of injury. However, the results from bioassay experiments should be considered only as indicative, because damage exhibited in a bioassay may not reflect yield loss in crop fields. It should be noted, however, that residual effects of herbicides may reduce growth and/or yield in more advanced stages than those considered by seedling bioassays because of the movement of herbicides in soil.

The main implication of this research is that applying the combination of imazamox plus imazapyr in sunflower is safer than imazapyr alone. In addition, barley was more sensitive than other winter cereals, particularly to imazapyr. However, 300 mm rainfall between application and the sowing was enough to avoid phytotoxic effect when herbicides were applied

Table 7. Shoot and root dry weight for oat and wheat grown in soil samples[a] at Tres Arroyos (2009–2010).

Herbicide	Rate	Shoot dry weight	Root dry weight
Oat	g ha^{-1}	mg	
Non-IMI control[b]		25.3	5.5
Imazapyr	160	21	4.2
Imazamox + imazapyr	33 + 15	23.2	5
Imazamox + imazapyr	66 + 30	20.3	4.4
Imazapyr	80	21.9	4.9
LSD[c]		NS	NS
Wheat			
Non-IMI control		29.9	8.2
Imazapyr	160	23.5	5.6
Imazamox + imazapyr	33 + 15	25.8	6.9
Imazamox + imazapyr	66 + 30	23.7	6.4
Imazapyr	80	25	6.7
LSD		4	1.2

[a] Samples were taken from a soil depth of 0 to 10 cm at 230 DAA (days after application).

[b] Herbicide treatment: fluorochloridone (375 g ai ha^{-1}) and acetochlor (900 g ai ha^{-1}). Abbreviation: IMI, imidazolinone.

[c] For each crop, data were analyzed by ANOVA regarding the randomized complete block design. Means were separated using Fisher's protected LSD ($P < 0.05$).

at recommended rates. Although the technology of IR crops is a highly effective means to help control weeds in sunflower, it must be used carefully because of the high probability to select for resistant biotypes of different types of weeds to this group of herbicides.

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