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Tillage Affects Imazamox Carryover in Yellow Mustard

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Farmers grow crops in the dryland region of the Pacific Northwest (PNW) using tillage practices ranging from moldboard plowing to no-tillage. The objective of this study was to determine the effect of tillage on persistence of imazamox herbicide in intermediate and high precipitation zones of the inland PNW. Along with a nontreated control, imazamox was applied to imidazolinone-tolerant winter wheat in the fall and spring at one, two, and three times the maximum labeled rate at locations near Genesee, ID, Davenport, WA, and Pendleton, OR. Moldboard plow, chisel plow, and no-till tillage treatments were implemented soon after wheat harvest and yellow mustard was planted the following season to determine crop response. Experiments were conducted at each location in 2005 to 2007 and 2006 to 2008. There were significant location by year and year and location interactions. There was no significant tillage by imazamox rate interaction, except at Pendleton in year 2, for all measured yellow mustard responses (crop injury, biomass, and yield). Genesee was colder than Pendleton and had more precipitation than Davenport, resulting in more injury to yellow mustard at Genesee than at Pendleton but less than at Davenport. Davenport had greater injury than the other two locations, likely due to lower soil pH, higher organic matter (OM), and cooler, drier climate, which allowed imazamox to persist longer in the soil. Overall, Pendleton had the least yellow mustard injury, which likely was related to its warmer, wetter climate and the concomitant rapid soil dissipation of imazamox. Tillage did not reduce the persistence of imazamox. Yellow mustard had the lowest injury and had greater mature biomass and seed yield in no-till seeded plots when averaged across imazamox rates compared to moldboard and chisel-plowed plots.
Nomenclature: Imazamox; yellow mustard, *Sinapis alba* L. 'IdaGold'; winter wheat, *Triticum aestivum* L.
Key words: Soil pH, precipitation, seed yield, soil persistence.

Los agricultores cultivan en la región seca del Pacífico Noroeste (PNW), usando prácticas de labranza que van desde el uso del arado de vertedera al sistema de cero labranza. El objetivo de este estudio fue determinar el efecto de la labranza sobre la persistencia del herbicida imazamox en zonas de precipitación intermedia y alta del interior del PNW. Además de un testigo no tratado, se aplicó imazamox a trigo de invierno tolerante a imidazolinone en el otoño y primavera, a una, dos y tres veces la dosis máxima recomendada, en sitios cercanos a Genesee, ID, Davenport, WA, y Pendleton, OR. Los tratamientos con arado de vertedera, arado de cinceles y cero labranza fueron implementados inmediatamente después de la cosecha de trigo y en la siguiente temporada se sembró *Synapis alba* para determinar la respuesta del cultivo. Los experimentos se realizaron en cada sitio en 2005–2007 y 2006–2008. Hubo interacciones significativas de sitio por año y de año y sitio. No hubo ninguna interacción significativa de tipo de labranza por dosis de imazamox, excepto en Pendleton en el año 2, para todas las respuestas cuantificadas de *S. alba* (el daño al cultivo, la biomasa y el rendimiento). Hizo más frío en Genesee que en Pendleton y en Genesee hubo más precipitación que en Davenport, originando más daño a *S. alba* en Genesee que en Pendleton, pero menor que en Davenport. Davenport tuvo mayor daño que en los otros dos sitios, probablemente debido al pH de suelo más bajo, mayor OM y un clima más frío y seco, lo cual permitió que imazamox persistiera mayor tiempo en el suelo. En general, Pendleton reportó el menor daño de *S. alba,* lo cual probablemente fue atribuido a su clima más cálido y húmedo y a la concomitante y rápida disipación de imazamox en el suelo. La labranza no redujo la persistencia de imazamox. En las parcelas sembradas bajo el sistema de cero labranza, *S. alba* sufrió el menor daño, tuvo mayor biomasa madura y mayor rendimiento de semilla, cuando se promedió a través de todas las dosis de imazamox, en comparación con las parcelas donde se usó el arado de vertedera o el arado de cinceles.

Herbicides are applied at least once each year to the majority of all annual croplands in the dryland wheat production areas of the Pacific Northwest (PNW) (Hanson et al. 2004). Several of these herbicides have residual activity in the soil, which provides extended weed control during the cropping season. However, some of these herbicides also persist more than one growing season and injure subsequent rotational crops. Farmers grow crops in the dryland region of PNW using tillage practices ranging from moldboard plowing to no-tillage, which can influence herbicide persistence (Hanson et al. 2004).

Herbicide dissipation rate, soil persistence, and potential for injury to rotational crops are major areas of research that are addressed before a new herbicide is labeled for use in a cropping system. However, research seldom is conducted to compare potential herbicide carryover across different tillage

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Table 1. Previous crop history in 2004 and 2005, and soil characteristics for imazamox soil persistence field studies in 2005 to 2007, and 2006 to 2007, respectively.

Location and year	Previous crop	Series	Texture	Classification	CEC	pH	OM[a]	Sand	Silt	Clay
					cmol(+) kg^{-2}		———	———	% ———	———
2005 to 2007 (Year 1)										
Genesee, ID	No-till spring barley	Palouse	Silt loam	Pachic Ultic Haploxerolls	20	5.1	3.5	23	55	23
Davenport, WA	Chemical fallow	Hanning	Silt loam	Pachic Argixerolls	16	4.9	4.1	29	61	10
Pendleton, OR	Chemical fallow	Walla Walla	Silt loam	Typic Haploxerolls	17	5.2	2.6	27	58	15
2006 to 2008 (Year 2)										
Genesee, ID	No-till spring wheat	Naff-Palouse	Silt loam	Typic Argixerolls	28	6.0	4.0	24	54	23
Davenport, WA	No-till spring wheat	Hanning	Silt loam	Pachic Argixerolls	19	4.9	3.1	13	75	13
Pendleton, OR	Chemical fallow	Walla Walla	Silt loam	Typic Haploxerolls	20	5.0	2.4	29	58	14

[a] Abbreviation: OM, organic matter.

practices and environments. Studies conducted in northern Idaho across a number of tillage systems anecdotally showed that several wheat herbicides had lowest rotational crop carryover injury with moldboard plowing and greatest injury in direct-seeded systems (Rauch and Thill 2003). Rotational crop carryover injury was intermediate in a minimum tillage experiment. Tillage increases herbicide decomposition indirectly through increased microbial and chemical breakdown (Curran 1998). In a study conducted in Iowa on corn (*Zea mays* L.), carryover injury was more severe following chisel plowing than moldboard plowing, suggesting that the herbicide dissipated more rapidly with the more intensive tillage (Hartzler et al. 1989).

The potential for a herbicide to persist and injure rotational crops is due to complex interactions among herbicide characteristics, soil type, seasonal difference in soil moisture, and temperature, tillage, and the sensitivity of the rotational crop to the herbicide (Rainbolt et al. 2001; Shinn et al. 1998). The complexities of these interactions preclude all but a few generalizations. Thus, it is necessary to determine herbicide persistence in specific environments, crops and tillage systems.

Imazamox is an imidazolinone herbicide that controls weeds by inhibiting acetohydroxyacid synthase (AHAS) (EC 4.1.3.18), also called acetolactate synthase (ALS), a key enzyme in the biosynthesis of branched-chain amino acids isoleucine, leucine, and valine (Shaner et al. 1984). Imazamox is labeled for selective control of jointed goatgrass (*Aegilops cylindrical* Host), downy brome (*Bromus tectorum* L.), wild oat (*Avena fatua* L.), Italian ryegrass (*Lolium multiflorum* Lam.), and other weeds in imidazolinone-tolerant winter wheat (Rainbolt et al. 2004). It reportedly can persist in soil from 3 to 26 mo and can adversely affect the growth of rotational crops such as barley (*Hordeum vulgare* L.), canola (*Brassica napus* L.), and yellow mustard (Ball et al. 2003; Hanson et al. 2004).

The purpose of this study was to determine the response of yellow mustard to imazamox herbicide persistence under conventional, minimum, and direct-seed tillage systems in intermediate and high precipitation zones of the inland PNW. Imazamox was selected as a model herbicide for these studies because it is used widely to control weeds in Pacific Northwest winter wheat production systems that utilize various tillage systems. Yellow mustard was used as the field bioassay indicator crop because of its high sensitivity to imazamox residue in soil.

Materials and Methods

Field studies were conducted at the University of Idaho Kambitsch Research Farm near Genesee, ID; the Columbia Basin Agricultural Research Center near Pendleton, OR; and the Washington State University Wilke Research Farm near Davenport, WA during 2005 to 2007 (year 1) and 2006 to 2008 (year 2) to determine the response of yellow mustard to imazamox persistence under conventional, minimum, and direct-seed tillage systems in precipation zones characterized in the dryland farming regions of the PNW as low (about 300 to 400 mm yr^{-1}), and high (500 to 600 mm yr^{-1}) annual precipitation zones. The immediate previous crop and soil characteristics for both years and all locations are listed in Table 1. All sites had been in a no-till system for at least 3 yr prior to establishing the studies. The monthly total precipitation and monthly average temperature for 2005 to 2008 for each of the three sites are given in Figure 1. Experiments in year 1 and 2 at each location were located within 100 to 500 m of one another. Imidazolinone-tolerant soft white winter wheat (ORCF-101) was direct-seeded (no-till) in the fall at 112 kg ha^{-1} at Davenport using a Fabro no-till drill (Fabro Enterprises Limited, Swift Current, SK) with 18-cm row spacing, at Genesee using a Flexi-coil 8000 NT Air Seeder (Flexi-Coil, Saskatoon, SK) with 25-cm row spacing, and at Pendleton using a John Deere 1560 no-till drill (John Deere Headquarters, Moline, IL 61265) with 18-cm row spacing (Table 2).

The field trials were designed as a randomized complete, split-block with four replications. Whole plot size at Genesee was 4.9 by 10.7 m for the conventional tillage treatments and 4.9 by 8.5 m for the minimum tillage and direct-seed treatments. Whole plot size was 4.6 by 9.1 m at Pendleton and 4.9 by 9.1 m at Davenport for all tillage treatments. There were seven herbicide treatments in this experiment: an untreated control, fall applications of imazamox at 53, 105, or 157 g ha^{-1} and spring applications at the same rates. The specific imazamox rates represented 1×, 2×, and 3× the maximum labeled rate of imazamox for a single application timing. Fall applications were made to three- to four-leaf winter wheat, while the spring applications were made to five- to six-leaf, two- to three-tiller winter wheat. Imazamox was applied with 2.5% v/v of liquid fertilizer (32% urea ammonium nitrate) and 0.25% v/v of a nonionic surfactant. Imazamox treatments were applied at Genesee with a CO_2 pressurized backpack sprayer calibrated to deliver 94 ha^{-1} at

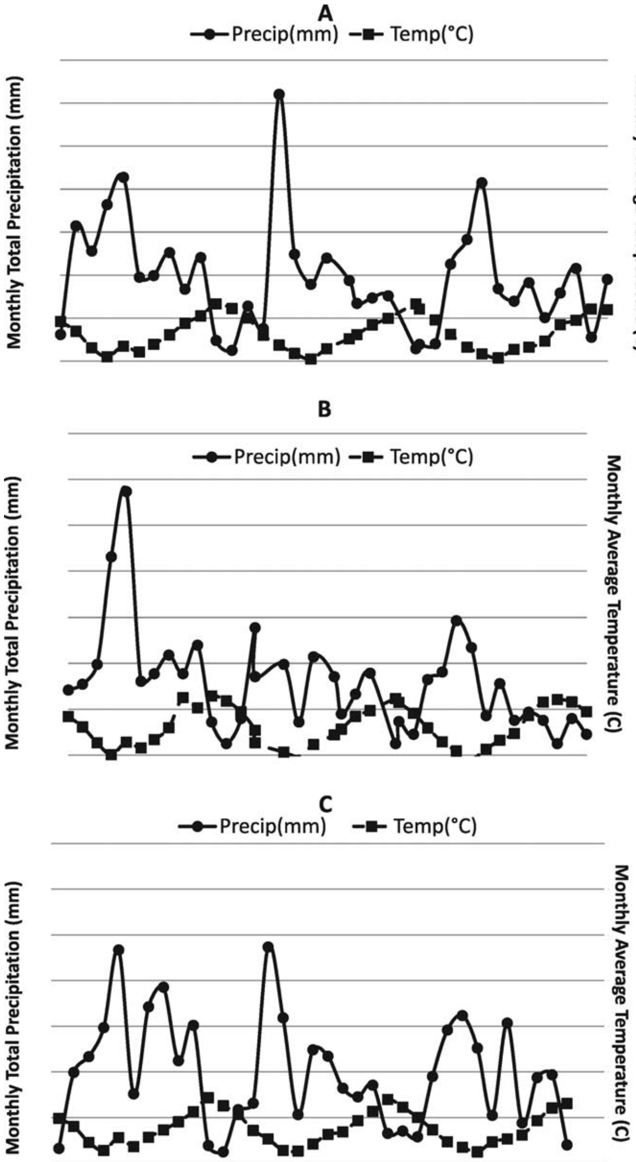

Figure 1. Monthly total precipitation and monthly average temperature for 2005 to 2008 in (A) Genesee, ID, (B) Davenport, WA, and (C) Pendleton, OR.

241 kPa. Imazamox was applied at Pendleton with a small plot tractor sprayer calibrated to deliver 94 L ha^{-1} at 138 kPa and at Davenport with a small-plot tractor sprayer calibrated to deliver 94 L ha^{-1} at 241 kPa.

An application of fluroxypyr at 14 g ae ha^{-1}, bromoxynil at 281 g ai ha^{-1}, and MCPA 281 g ae ha^{-1} plus 0.25% v/v nonionic surfactant was applied to wheat at Davenport during year 1 and at Genesee both years to control remaining broadleaf weeds.

The three tillage treatments were no-tillage, minimum tillage using a chisel plow, and conventional tillage using a moldboard plow. All conventional and minimum tillage treatments were tilled about 25 cm deep with the appropriate tillage tool in the fall following wheat harvest. Conventional and minimum tillage treatments then received secondary tillage with a field cultivator in the spring prior to seeding yellow mustard. At the Pendleton site, about 80% of the winter wheat residue was removed from the no-tillage plots following wheat harvest to facilitate seeding the following spring. 'IdaGold' yellow mustard, an important, rotational oil seed crop in dryland regions of the PNW was seeded at 9 kg ha^{-1} at Pendleton and 11 kg ha^{-1} at Genesee and Davenport using a Fabro no-till drill with rows spaced 18 cm apart. The drill was adjusted for each tillage treatment so that seed was placed approximately 1.5 cm deep.

The following maintenance pesticides were applied to yellow mustard for year 1 studies: lambda-cyhalothrin {[1a(*S**),3a(*Z*)]-(±)-cyano-(3-phenoxyphenyl)methyl-3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylate} at 34 g ha^{-1} was applied at Pendleton; 1,121 g ha^{-1} carbaryl {1-naphthyl N-methylcarbamate} and 45 g ha^{-1} bifenthrin insecticide {(2 methyl[1,1'-biphenyl]-3-yl) methyl 3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethyl-cyclopropanecarboxylate} were applied at Genesee. Quizalofop was applied at 54 g ha^{-1} plus 0.25% v/v nonionic surfactant (R-11 [Alkylphenol ethoxylate, butyl alcohol, dimethylpolysiloxane], Wilbur-Ellis Co., Fresno, California 93755) at Davenport for downy brome control. Clopyralid was applied at 105 g ae ha^{-1} plus 0.25% v/v nonionic surfactant at Genesee for broadleaf weed control. During year 2 at Genesee, only lambda-cyhalothrin at 34 g ha^{-1} was applied.

Yellow mustard visible injury (0% = no injury and 100% = complete plant death) was evaluated 14, 21, and 56 d after emergence (DAE); however, data are only presented from the 56 DAE evaluation because peak injury occurred on this date. Yellow mustard plants were counted 21 DAE in two 1-m sections of row randomly located within each plot. Above-ground crop biomass was collected from two 1-m sections of row randomly located within each plot when the untreated control plots reached 50% flowering. Yellow mustard plants were counted, cut at the soil surface, placed in paper bags, dried at 60 C for 72 h, then weighed. Yellow mustard seed was harvested using a small plot combine and yield was determined for each plot. Because both temporal and spatial variability was evident across years and locations, responses were evaluated as percentages of the untreated check treatments. Treatment effects were assessed using analysis of variance with subsequent mean separation using Fischer's LSD and single degree of freedom contrasts. All statistical computations were carried out using PROC GLM, fixed effect, SAS® version 9.1 (SAS 2007).

Results and Discussion

Location and Year Environmental Differences. The three research sites differed in temperature and precipitation (Figure 1). Davenport has a cool climate with low precipitation; Pendleton has a warmer climate with high precipitation; and Genesee's annual average temperature is intermediate compared to the other two sites and has high precipitation. The following average temperature and total rainfall data are from the planting of the winter wheat to the harvest of the yellow mustard (21 to 24 mo). Average temperatures at Pendleton were 10.7 C and 9.8 C for years 1 and 2, respectively; Genesee

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Table 2. Dates of field operations for imazamox soil persistence studies near Genesee, ID, Davenport, WA, and Pendleton, OR conducted in 2005 to 2007 (year 1) and 2006 to 2008 (year 2).

	Genesee		Davenport		Pendleton	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Winter wheat seeded	October 7, 2005	October 12, 2006	September 13, 2005	September 12, 2006	October 14, 2005	October 16, 2006
Fall imazamox application	November 2, 2005	December 14, 2006	October 18, 2005	October 27, 2006	November 2, 2005	November 20, 2006
Spring imazamox application	April 25, 2006	May 11, 2007	April 26, 2006	April 26, 2007	March 3, 2006	March 22, 2007
Winter wheat harvest	August 15, 2006	August 13, 2007	August 9, 2006	August 1, 2007	July 26, 2006	July 24, 2007
Primary tillage	October 31, 2006	October 23, 2007	October 24, 2006	October 23, 2007	October 11, 2006	October 18, 2007
Yellow mustard seeded	April 20, 2007	May 12, 2008	April 11, 2007	May 2, 2008	March 23, 2007	April 1, 2008
Yellow mustard plant counts	May 24, 2007	June 18, 2006	June 20, 2007	June 4, 2008	April 27, 2007	May 16, 2008
Yellow mustard biomass	June 27, 2007	June 26, 2008	June 20, 2007	June 19, 2008	June 1, 2007	June 5, 2008
Yellow mustard injury evaluation	June 29, 2007	July 7, 2008	June 20, 2007	June 25, 2008	June 4, 2007	June 25, 2008
Yellow mustard harvest	August 28, 2007	August 28, 2008	August 6, 2007	September 9, 2008	July 31, 2007	July 31, 2008

averaged 8.4 C and 7.8 C for years 1 and 2, respectively; and Davenport averaged 7.6 C and 7.2 C for years 1 and 2, respectively. Total precipitation at Pendleton was 858 mm and 724 mm for years 1 and 2, respectively; Genesee precipitation was 819 mm and 730 mm for years 1 and 2, respectively; and Davenport precipitation was 721 mm and 523 mm for years 1 and 2, respectively.

Yellow Mustard. Yellow mustard visible injury, biomass, and yield data are expressed as a percentage of the untreated control and are presented within year and by location because there was a significant location by year interaction ($P < 0.05$). There were no significant herbicide by tillage interactions for measured variables for any year 1 locations or at Davenport and Genesee in year 2. However, there was a significant herbicide rate by tillage interaction for the Pendleton site in year 2.

The imazamox treatments applied to wheat affected injury, biomass, and seed yield of yellow mustard, but not plant counts 21 DAE (data not shown). Observed yellow mustard injury included stunting, reduced biomass production, and delayed flowering. Overall, yellow mustard injury from imazamox persistence, averaged across all herbicide treatments, was greatest at Davenport in year 2 (82%) and least at Pendleton in year 1 (24%) (Table 3). Average injury for all other locations and years ranged from 62 to 66%. Averaged across years and locations, injury was always least when imazamox was applied at the 1× rate in the fall (37%), followed by the 1× rate in the spring (48%), 2× rate in the fall (57%), 2× rate in the spring (69%), 3× rate in the fall (71%), and 3× rate in the spring (81%). The tillage by imazamox rate interaction was significant ($P = 0.0001$) for yellow mustard injury only at

Table 3. Yellow mustard visible crop injury (56 d after emergence), biomass, and seed yield by application timing and rate expressed as a percentage of the untreated control in imazamox soil persistence studies near Genesee, ID, Davenport, WA, and Pendleton, OR conducted in 2005 to 2007 (2007) and 2006 to 2008 (2008).

Imazamox		Genesee		Davenport		Pendleton	
		2007	2008	2007	2008	2007	2008
Rate[a]	Timing	Injury (%)					
1×	Fall	42	48	41	48	1	39
2×	Fall	64	64	50	80	21	64
3×	Fall	82	79	60	89	40	73
1×	Spring	50	50	57	81	5	45
2×	Spring	71	71	81	95	27	68
157	Spring	86	81	91	98	49	82
$LSD_{0.05}$		11	12	12	8	7	9
		Biomass (%)					
1×	Fall	85	68	91	38	70	44
2×	Fall	39	45	73	57	45	33
3×	Fall	22	25	53	12	35	22
1×	Spring	101	43	55	34	65	24
2×	Spring	45	29	40	8	38	7
157	Spring	23	32	13	1	22	7
$LSD_{0.05}$		35	21	25	NS	11	16
		Yield (%)					
1×	Fall	81	66	107	69	112	57
2×	Fall	46	36	96	15	82	15
3×	Fall	16	19	74	11	71	10
1×	Spring	75	51	83	25	115	50
2×	Spring	38	26	48	6	77	18
157	Spring	33	14	28	0	61	7
$LSD_{0.05}$		36	24	23	15	19	12

[a] Rate: 1×, 53 g ai ha^{-1}; 2×, 105 g ai ha^{-1}; 3×, 157 g ai ha^{-1}.

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Table 4. The effect of tillage and imazamox treatment at Pendleton, OR, on yellow mustard injury, biomass, and yield expressed as a percentage of the untreated control in 2008.

Imazamox		Tillage Treatment			
		Conventional	Minimum	Direct-seed	*Means*
Rate [a]	Timing	Injury (%)			
1×	Fall	50	35	31	*39 d*
2×	Fall	81	65	45	*64 c*
3×	Fall	92	71	56	*73 b*
1×	Spring	38	46	51	*45 d*
2×	Spring	44	80	81	*68 bc*
3×	Spring	70	84	93	*82 a*
		62 a [b]	*64 a*	*60 a*	
		Biomass (%)			
1×	Fall	12	40	78	*44 a*
2×	Fall	2	34	62	*33 ab*
3×	Fall	1	24	42	*22 bc*
1×	Spring	31	18	22	*24 b*
2×	Spring	13	2	6	*7 c*
3×	Spring	8	9	2	*7 c*
		11 b	*21 ab*	*35 a*	
		Yield (%)			
1×	Fall	43	48	79	*57 a*
2×	Fall	8	15	26	*15 b*
3×	Fall	5	18	8	*10 b*
1×	Spring	68	39	45	*50 a*
2×	Spring	40	9	5	*18 b*
3×	Spring	8	11	1	*7 b*
		29 a	*23 a*	*27 a*	

[a] Rate: 1×, 53 g ai ha^{-1}; 2×, 105 g ai ha^{-1}; 3×, 157 g ai ha^{-1}.

[b] Means followed by the same letter are not significantly different (P = 0.05).

Pendleton in year 2 (Table 4). In this case, treatment means followed the same general trends as the other locations, but when imazamox was applied in the fall at the 2× rate, injury was 81% in conventional tillage plots and 65 and 45% in the minimum and direct-seed plots, respectively. However with the spring treatment at the same rate of imazamox, injury was least in the conventionally tilled plots (44%) and greatest in the minimum and direct-seeded plots (80 to 81%).

Fall-applied imazamox treatments injured yellow mustard less than spring-applied treatments, except at the Genesee location in both years where there was no difference in visible injury between fall- and spring-applied imazamox (Table 5). Injury ranged from 64 to 69% in year 1 and 62 to 64% in year 2 for fall and spring treatments, respectively, at Genesee. Injury from fall vs. spring treatment ranged from 21 to 27% at Pendleton in year 1 to 72 to 91% at Davenport in year 2 (Table 5). Greater injury from the spring-applied imazamox treatments likely was caused by the shorter interval between herbicide applications to winter wheat and seeding of yellow mustard. The 1× rate of imazamox always caused less injury (42%) compared to the 2× (63%) or the 2× and 3× rates combined (69%) (Table 5). This was expected because higher rates of imazamox would exacerbate the injury, and the plantback interval for the 1× rate listed on the imazamox label for yellow mustard is 26 mo (Hanson et al. 2004).

Yellow mustard biomass averaged across all rates and application timings was affected least at Davenport in year 1 (54% of the untreated control) and most at Pendleton and Davenport in year 2 (23 and 25% of the untreated control) (Table 3). Average biomass in all other locations and years ranged from 40 to 54% of the untreated control. Biomass was reduced most when imazamox was applied at the 3× rate in the spring (16% of the untreated control), followed by the 2× rate in the spring and the 3× rate in the fall (28%), 2× rate in the fall (49%), 1× rate in the spring (54%), and 1× rate in the fall (66%).

The tillage by imazamox rate interaction for biomass was significant (P = 0.0015) at Pendleton in year 2. Fall-applied imazamox in the conventional tillage treatments had the least biomass compared to minimum and direct-seed treatments, whereas biomass reduction was similar among tillage treatments with spring-applied imazamox (Table 4). Fall-applied imazamox treatments had 167% more yellow mustard biomass than spring-applied treatments, except at the Genesee location in year 1 and Davenport in year 2 (Table 5). Biomass averaged 49 and 56% (Genesee in year 1) of the untreated control and 36 and 14% (Davenport in year 2) for fall and spring treatments, respectively. The 1× rate of imazamox usually had significantly more biomass (60% of the untreated control) compared to the 2× (38%) or the 2× and 3× rates combined (31%).

On average, yellow mustard yield was affected least at Pendleton in year 1 (86% of the untreated control) and most at Davenport in year 2 (21%) (Table 3). Average yield at all other locations ranged from 26 to 73% of the untreated control. Yield usually was reduced least when imazamox was applied at the 1× rate in the fall (82% of the untreated control), followed by the 1× rate in the spring (67%), 2× rate in the fall (48%), 2× rate in the spring (36%), the 3×

Table 5. Yellow mustard visible crop injury, biomass, and seed yield raw means in imazamox soil persistence studies near Genesee, ID, Davenport, WA, and Pendleton, OR, conducted in 2005 to 2007 (2007) and 2006 to 2008 (2008). Data are expressed as a percentage of the untreated control.

	Genesee		Davenport		Pendleton	
Contrasts	2007	2008	2007	2008	2007	2008
	%					
Injury						
Fall/spring[a]	64/69	62/64	50/76***[d]	72/91**	21/27**	59/65**
1×/2×[b]	46/68***	46/66***	49/65***	64/87***	3/24***	42/66***
1×/2× and 3×[c]	46/77***	46/72***	49/71***	64/90***	3/34***	42/72***
Biomass						
Fall/spring[a]	49/56	49/34*	72/36***	36/14	50/41**	33/12***
1×/2×[b]	94/42***	58/36**	73/57	36/33	68/41***	34/20**
1×/2× and 3×[c]	93/32***	58/34***	73/45***	36/20	68/35***	34/17**
Yield						
Fall/spring[a]	47/47	41/33	98/53***	32/10***	88/84	27/25
1×/2×[b]	80/38**	61/32**	96/80**	47/11***	113/79***	54/17***
1×/2× and 3×[c]	80/31***	61/26***	96/66***	47/8***	113/73***	54/13***

[a] Numbers to the left of the slash represent means for fall, and numbers to the right of the slash represent means for the spring.

[b] Numbers to the left of the slash represent means for 1× (53 g ai ha^{-1}), and numbers to the right of the slash represent means for 2× (105 g ai ha^{-1}).

[c] Numbers to the left of the slash represent means for 1× (53 g ai ha^{-1}), and numbers to the right of the slash represent means for 2× (105 g ai ha^{-1}) and 3× (157 g ai ha^{-1}).

[d] Contrasts significant at the *P = 0.05 to 0.01, **P= 0.01 to 0.001, ***P = ≤ 0.001 levels.

rate in the fall (34%), and the 3× rate in the spring (24%). The tillage by imazamox rate interaction was significant (P = 0.0006) only at Pendleton in year 2 (Table 4). Usually, yield was lowest in conventionally tilled treatments compared to minimum and direct-seed treatments applied in the fall. The opposite was true with spring-applied treatments, as was the case for crop biomass.

Fall-applied imazamox treatments had greater yellow mustard seed yield (61% of the untreated control) than spring-applied treatments (43%), except at the Genesee location during both years (Table 5). The 1× rate of imazamox always produced more seed yield (75% of the untreated control) compared to the 2× (43%) or the 2× and 3× rates combined (36%).

When data were averaged over imazamox treatments, yellow mustard injury was not different among tillage treatments at Genesee and Pendleton in year 2 and Davenport in year 1 (Table 6). Yellow mustard injury was greater in conventional than in minimum tillage at Davenport in year 2 (84 vs. 79%). At Pendleton in year 1, injury was greatest in conventionally tilled plot (32%) and least in direct-seed plots (16%). Injury was greatest in minimum tillage plots (73%) and least in conventionally tilled plots (58%) at Genesee in year 1. Injury differed little among tillage treatments and was 59, 60, and 63% in direct-seeded, conventional, and minimum tilled plots, respectively, when averaged over herbicide treatments, locations, and years.

Yellow mustard biomass was not affected by tillage treatment at all locations and years, except at Pendleton in year 1 (Table 6). In year 1 at Pendleton, yellow mustard biomass was greatest in direct-seed plots (62% of the untreated control), where nonstanding wheat residue was removed after wheat harvest, and the least in the conventionally tilled plots (33%). Averaged over all locations and years, biomass was 55% of the untreated control in direct-seeded plots and 32 to 33% in the conventional and minimum tillage plots.

Averaged over imazamox treatments, yellow mustard seed yield was not affected by tillage treatment at Genesee and Pendleton in year 2 or at Davenport in both years (Table 6). At Genesee in year 1, seed yield was affected least in the conventionally tilled plots (66% of the untreated control) and most in the minimum tillage plots (31%). Seed yield was highest in the direct-seed plots at Pendleton in year 1 (114% of the untreated control) and the least in the conventionally tilled plots (60%). When averaged over herbicide treatments, locations, and years, yield was 55% of the untreated control in the direct-seeded plots, and was 45 to 46% in minimum and conventionally tilled plots, which is consistent with aboveground biomass results.

There was no tillage by imazamox rate interaction for five of the six location years when yellow mustard was used as an imazamox-sensitive indicator. These findings show that tillage did not enhance the dissipation of imazamox herbicide. In fact, compared to their respective untreated controls, yellow mustard usually was injured least, and the biomass and seed yield in direct-seeded plots treated with imazamox were greater than or equal to moldboard and chisel-plowed plots.

The 2005 to 2008 imazamox labels list a 3-mo plantback restriction on non-Clearfield wheat, whereas the most recent label has a non-Clearfield wheat rotational interval based on pH, moisture, and geographic location in the United States (Anonymous 2009). For example, in selected counties in northern Idaho (Benewah, Bonner, Boundary, Clearwater, Idaho, Kootenai, Latah, Lewis, Nez Perce, and Shoshone), all wheat-producing counties in eastern Washington, and all counties in Oregon except Malheur, the plantback for non-Clearfield wheat is based on pH and moisture (> 254 mm

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Table 6. Yellow mustard crop injury, biomass, and seed yield by tillage expressed as a percentage of the untreated control in imazamox soil persistence studies near Genesee, ID, Davenport, WA, and Pendleton, OR conducted in 2005 to 2007 (2007) and 2006 to 2008 (2008).

Tillage	Genesee		Davenport		Pendleton	
	2007	2008	2007	2008	2007	2008
	%					
Injury						
Conventional	58	67	56	84	32	62
Minimum	73	70	67	79	23	64
Direct-seed	69	59	67	83	16	60
$LSD_{0.05}$	10	NS	NS	4	10	NS
Biomass						
Conventional	55	38	53	6	33	11
Minimum	37	29	49	15	42	21
Direct-seed	65	55	61	54	62	35
$LSD_{0.05}$	NS	NS	NS	NS	9	NS
Yield						
Conventional	66	28	70	15	60	29
Minimum	31	30	81	23	85	23
Direct-seed	45	50	68	26	114	27
$LSD_{0.05}$	25	NS	NS	NS	14	NS

moisture and pH $>$ 6.2 is 3 mo, and $<$ 254 mm moisture or pH $<$ 6.2 is 15 mo). However, for barley there is an added tillage requirement ($>$ 457.2 mm moisture and pH $>$ 6.2 has a plantback of 9 mo whether moldboard plowed or not and $<$ 457.2 mm moisture or pH $<$ 6.2 is 18 mo without moldboard plowing and 9 mo with moldboard plowing). These same plantback restrictions will affect yellow mustard, the bioassay indictor crop used in these experiments.

Moisture, temperature, and pH differences among the study sites affected persistence of imazamox. Davenport likely had more yellow mustard injury than the other two sites because of lower soil pH, higher OM, and cooler, drier climate. These factors allow imazamox to persist longer in the soil. Pendleton had the least injury, which likely was related to its warmer, wetter climate. Studies done with imidazolinone herbicides have shown that carryover is more likely in soils with medium to high OM content and low pH (Loux and Reese 1993). The persistence of the acid form of imidazolinones herbicides generally is greater at cooler temperatures because it is more rapidly metabolized by microorganisms to inactive degradation products at warmer soil temperatures (Malefyt and Quakenbush 1991). Additionally, herbicide degradation rates can be increased under moist soil conditions, which can reflect increased biological activity (Hurle and Walker 1980). Also at Pendleton, the direct-seeded plots showed the least injury and the highest yield compared to other tillage treatments. This might be due to the removal of winter wheat residue from the direct-seed plots at that location, which allowed the soil surface to warm in the late winter and early spring. The warmer soil likely increased the rate of microbial degradation of imazamox compared to other tillage treatments. Microbial degradation under aerobic conditions is the primary degradation mechanism of imidazolinones (Basham and Lavy 1987). Conditions that tend to favor microbial activity, such as warm, moist soils, also are the conditions under which the imidazolinones are most rapidly degraded (Mangels 1991).

Based on these findings, the reliance on moldboard plowing to reduce persistence or carry-over of imazamox might not be a reliable practice to reduce injury in sensitive rotational crops, such as non-Clearfield wheat, barley, or yellow mustard. Farmers and field consultants must consider several variables, such as tillage practices, previous precipitation patterns and amounts, seasonal temperature variations, and soil pH and OM variability within and among fields to better predict potential imazamox injury to rotational crops.

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