Article

Cover Crop Tolerance Following Commonly Applied Herbicides in Silage Corn and Soybean

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Simple Summary: A Simple summary goes here.

Abstract: A single paragraph of about 200 words maximum. For research articles, abstracts should give a pertinent overview of the work. We strongly encourage authors to use the following style of structured abstracts, but without headings: 1) Background: Place the question addressed in a broad context and highlight the purpose of the study; 2) Methods: Describe briefly the main methods or treatments applied; 3) Results: Summarize the article's main findings; and 4) Conclusion: Indicate the main conclusions or interpretations. The abstract should be an objective representation of the article, it must not contain results which are not presented and substantiated in the main text and should not exaggerate the main conclusions.

Keywords: keyword 1; keyword 2; keyword 3 (list three to ten pertinent keywords specific to the article, yet reasonably common within the subject discipline.).

1. Introduction

With interest in conservation agricultural practices, there has been an increase in growers' adoption of cover crops in the United States (US) [1]. Cover crops is promoted as a conservation management practice to increase diversity on corn-soybean rotation cropping systems. Cover crop benefits includes reduce soil erosion, scavenge or provide nutrients, suppress weeds, and improve overall soil quality [2–4]. Implementing cover crops in the upper-Midwest US region is challenging, especially at after crop harvest. Planting and establishing cover crops were listed as a major challenge for Nebraska's growers, follow by cover crop termination and herbicide carryover [1]. Although planting is a major challenge for cover crop establishment due to short growing season before winter, herbicide carryover from previous cash crop is an emerging challenge in conventional cropping systems.

Herbicides are a foundation FOR weed managment in conventional US cropping system. The use of residual herbicide has been promote as a management strategy to minimize the impact of herbicide resistant weeds, which are currently a major threat to cropping-systems sustainabily in the US [5]. For example, because of residual activity, preemergence (PRE) herbicides has proven to reduce early germinate weed populations, which minimize early-season crop-weed competition and promote a timely postemergence (POST) application window [6]. Thus, the use of resisual herbicide in on increase and it brings multiple benefits for managing weeds. However, long persistence of herbicide in soil may negatively affect establishment of proceeding crops several weeks to months after herbicide application. Therefore, the complexity of cover crops establishment may increase in conventional cropping systems.

The persistence of residual herbicides in soils can be affected by environmental conditions (e.g., rainfall and temperature), management practices (e.g., tillage, herbicide rate and application method), and soil properties (e.g., moisture, temperature, soil colloid properties, chemical reactions, pH, microbial population, soil texture and organic matter) [7]. For example, there is evidence that herbicide carryover potential on cover crops is greatly influenced by precipitation following herbicide application [8] and higher soil clay content (Kendig, et al. 1991). Because of multiple factors influencing herbicide carryover, it was documented that herbicide carryover impact on crops may vary over several growing seasons [8]. When herbicide carryover occurs, it is likely to affect the subsequent cash or cover crop in the form of stand reduction, visual observation of poor plant health and color, and/or a reduction of plant productivity usually noticed in reduction of vigor and biomass accumulation [9].

Several studies have documented the impact of herbicide carryover and persistence issues following herbicide application in corn and soybean [10–15]. With emerging adoption of cover crop after crop harvesting, it is likely that herbicide carryover may affect cover crop planting and establishment as well. For example, it was shown that residual herbicides applied to corn and soybean can persist in the soil longer than initially desired at the time of application and injure the following fall seeded cover crop [8,16]. In addition, the application of different residual herbicides may cause different responses on various cover crop species. Yu et al. [16] found that fall seeded cover crops had different responses to residual herbicides, including saflufenacil + dimethenamid-*P*, *S*-metolachlor + atrazine + mesotrione, and imazethapyr. Therefore, there is a need to expand research on the impact of herbicide (mixed or tank mixed) on cover crops establishment.

In the upper US Midwest and other geographies, growers commonly plant silage corn for forage. Growers are interested in using cover crops following silage corn for soil conservation value. In such cases, silage crop harvest as well as cover crop planting may occur earlier than grain crop, which shortener the gap between herbicide application on silage crop and cover crop planting, increasing the chances of cover crop injury due to herbicide carryover. There is minimal information available on the carryover effects of commonly applied herbicides on regularly used cover crops following silage corn and soybeans. The objective of this research was to determine if commonly applied herbicides in a silage corn or soybean cropping system adversely affect cover crop. We hypothesize that residual herbicide use might negatively affect fall seeded cover crops, including annual ryegrass (*Lolium multiflorum*), crimson clover (*Trifolium incarnatum*), radish (*Raphanus* spp), oat (*Avena fatua*), and oat/pea (*Pisum sativum*) mixture.

2. Materials and Methods

2.1. Plant Material and Site Description

Field experiments were conducted at the University of Wisconsin Arlington Agricultural Research Station near Arlington, WI (43.30 N, 89.33 W) during 2013 and 2014. The soil type was a Plano silt loam (fine silty, mixed, mesic Typic Argiudoll) soil with a pH of 6.3 and 3.4 % organic matter in 2013, and pH 6.85 with 3.35 % organic matter in 2014. Monthly precipitation and temperatures for 2013 and 2014 were recorded (Table 1). Fifteen herbicide treatments within each corn (Table 2) and soybean (Table 3) trial were arranged as a randomized complete block with four replications. Six cover crop species were randomly planted in perpendicular strips across the herbicide treatments within blocks. Prior to trial establishment, fields were in a corn-soybean crop rotation and were chisel-plowed the previous fall and were spring cultivated prior to crop planting.

Table 1. Monthly precipitation and mean air temperatures during 2013, 2014 and January through May 2015 compared to 30 year average at the Arlington Agriculture Research Station, Arlington, Wisconsin.

Month	Total Precipitation				Mean Air Temperature			
	30 yr Normal	2013	2014	2015	30 yr Normal	2013	2014	2015
January	29	49	4	5	-9	-7	-13	-8
February	33	33	15	2	-6.5	-7	-13	-11
March	48	51	23	13	-0.3	-4	-4	0.4
April	89	154	172	168	7	5	6	8
May	94	158	59	125	13	14	14	15
June	119	189	238		19	24	26	
August	99	42	65		20	26	26	
September	90	0.25	31		15	25	21	
October	65	50	65		9	9	8	
November	61	57	32		1	0.35	-3	
December	37	11	33		-6	-9	-3	

Hybrid corn planted in 2013 was DKC53-45 RIB (DEKALB, Bayer Crop Science, St Louis, MO) and in 2014 FS36RV4 RIB (FS InVision, FS Seeds, Bloomington, IL). Soybean variety in 2013 was AG 2031 (Asgrow, Bayer Crop Science, St. Louis, MO) and in 2014 was S22-S1 (Syngenta Seeds Inc., Greensboro, NC). Both corn and soybean trials were planted 3 June 2013 and 22 May 2014 using a 3 m wide vacuum planter (Model 1750, John Deere, Moline, IL). Herbicide plots were 3 m wide x 15 m long and included four 76-cm wide rows in both crops. Corn seeds were planted 3.8 cm deep at 81000 seed ha^{-1}, and soybean seeds were planted 2.5 cm deep at 385000 plants ha^{-1}.

2.2. Field experiments

Herbicide treatments were applied in PRE for both corn and soybean trials on 9 May 2013 and 22 May 2014. Early-POST (EPOST) herbicides were applied at V2 corn development stage on 18 June 2013 and 9 June 2014. Soybean applications in POST were applied at V3 soybean development stage and late-POST (LPOST) applications were applied at V4 corn development stage on 2 July 2013 and 23 June 2014. Herbicide treatments were applied with a CO2-pressurized back-pack sprayer at 4.8 km h^{-1} delivering 140 L ha^{-1} of spray solution at 172 kPa pressure using XR11002 flat-fan nozzles (Spraying Systems Co. Wheaton, IL). Corn and soybean plots also received two POST applications each year to minimize weed competition. For plot maintenance, glyphosate (Touchdown Total, Syngenta Crop Protection, Greensboro, NC) was applied at 1.17 kg acid equivalent (ae) per ha^{-1} and ammonium sulfate at 7.7 kg per 387.5 L of water. These POST maintenance herbicides were applied with a tractor mounted three-point sprayer with a 6 m boom delivering 140 L ha^{-1} of spray solution at 276 kPa pressure, using air induction extended range AIXR11002 (Spraying Systems Co., Wheaton, IL) flat-fan nozzles.

Both corn and soybean trials were harvested as forage with a self-propelled forage chopper on 8 September 2013 and 15 September 2014. Six different cover crop species and/or varieties were no-till seeded uniformly perpendicular across all herbicide treatments on 9 September 2013 and 17 September 2014. Cover crops were seeded using a 2.5 m wide no-till drill (Tye, AGCO, Duluth, GA) with three rows closed off to allow for six cover crops to be evenly spaced in the 15 m corn and soybean herbicide plots. To consistently plant the cover crops within the plots, real time kinetics (RTK) guidance (Auto Trac, John Deere, Moline, IL) was used. The cover crop plots were 1.95 meters wide with a row spacing of 19 cm. Cover crops planted were radish at 12.3 kg ha^{-1}, crimson clover at 11.2 kg ha^{-1}, winter rye at 134.4 kg ha^{-1}, 70% oat plus 30% peas mixture at 101 and 34 kg ha^{-1}, and two annual ryegrass varieties at 37 kg ha^{-1}. The annual ryegrass varieties included Bruiser and King. Winter rye and the 70% oats 30% pea mixture were planted 2.5 cm deep and crimson clover, radish, and annual ryegrass varieties were planted 0.6 cm deep.

Table 2. XXXXX

Herbicide	Trade name	Timing	Rate (g ai[e] ha-1)	Manufacturer
nontreated				
flumetsulam	Python	PRE	22.7	Corteva Agriscience
flumioxazin + pyroxasulfone	Fierce	PRE	21.7 + 27.5	Valent USA
saflufenacil + dimethenamid-*P*	Verdict	PRE	30.3 + 265.8	BASF Corporation
S-metolachlor + mesotrione	Zemax	PRE	758 + 75	Syngenta Crop Protection
acetochlor + flumetsulam + clopyralid	SureStart	EPOST	318.9 + 10.2 + 32.3	Corteva Agriscience
clopyralid	Stinger	EPOST	85.0	Corteva Agriscience
mesotrione	Callisto	EPOST	85.0	Syngenta Crop Protection
nicosulfuron	Accent Q	EPOST	13.9	Corteva Agriscience
rimsulfuron	Resolve	EPOST	7.1	Corteva Agriscience
rimsulfuron + thifensulfuron-methyl	Basis Blend	EPOST	1.9 + 0.9	Corteva Agriscience
simazine	Princep 4F	EPOST	907.1	Syngenta Crop Protection
tembotrione	Laudis	EPOST	37	Bayer Crop Science
topramezone	Impact	EPOST	7	AMVAC Corporation
S-metolachlor fb glyphosate + mesotrione	Zemax fb Halex GT	LPOST	426.6 + 426.6 + 42.7	Syngenta Crop Protection

Table 3. YYYYYYY

Herbicide	Trade name	Timing	Rate (g ai[e] ha-1)	Manufacturer
nontreated				
chlorimuron-ethyl	Classic	PRE	7.1	Corteva Agriscience
flumioxazin	Valor	PRE	36.2	Valent USA
flumioxazin + cloransulam-methyl	Gangster	PRE		Valent USA
metribuzin	Senhor	PRE	170.1	Bayer Crop Science
sulfentrazone	Spartan	PRE	113.4	BASF Corporation
sulfentrazone + metribuzin	Authority MTZ	PRE	61.2 + 91.9	FMC Corporation
pyroxasulfone	Zidua	PRE	72.3	Valent USA
acetochlor	Warrant	EPOST	510.3	Bayer Crop Science
cloransulam-methyl	First Rate	EPOST	7.1	Corteva Agriscience
fomesafen	Flexstar	EPOST	106.6	Syngenta Crop Protection
imazethapyr	Pursuit	EPOST	106.6	Syngenta Crop Protection
imazethapyr + glyphosate	Extreme	EPOST	6.6 + 21.0	BASF Corporation
lactofen	Cobra	EPOST	88.6	Valent USA
S-metolachlor	Dual II Magnum	EPOST	576.1	Syngenta Crop Protection

2.3. Data Collection

Cover crop biomass was collected on 4 November 2013 and 11 November 2014. The biomass harvest occurred before, but as close to, the first killing frost as best as could be predicted from weather forecasts in 2013 and 2014. Biomass was collected from 25 cm linear row in each subplot from an arbitrarily selected corner. Biomass samples were dried at 60 C until constant weight and weighed to the hundredth of a gram. Winter rye was the only cover crop to survive winter 2013 and 2014.

Cover crops were also evaluated for herbicide injury beginning one week after cover crop emergence and evaluated for three weeks total. Injury evaluation data included visual ratings and cover (digital imagery analysis). Injury accessment was performed using a scale from 0% to 100% in comparison to the nontreated. Comparison is based on plant chlorosis, reddish, whitening, necrosis, stunted, deformed and cupping leaves. In the 0-100% scale, 0% is a complete health and 100% a complete dead plant. The methods for cover analysis data collection were adapted from Purcell (2000). Digital images were taken at 91 cm above each subplot. A standard digital camera was mounted at a 70 angle on a 2.54 by 114 cm board. This board creates a stand for the camera to capture consistent photos of the plots. The camera was set to auto mode with zoom set to 0. These pictures were resized and renamed using FastStone Image Viewer (FastStone Soft, 2015). Once resized the pictures were analyzed to determine the percentage of green cover using Sigma Scan Pro (v. 5.0; SPSS Science, 1998)

Table 4. Anova Corn

Anova	Species					
	Bruiser annual rye	Crimson clover	King annual rye	Oat/Pea	Radish	Winter Rye
Biomass (g)			—— P-value ——			
herbicide	0.9189	0.9216	0.2809	0.3490	0.9082	0.0622
year	0.0000	0.0000	0.2981	0.0000	0.0000	0.0003
herbicide*year	0.5099	0.8763	0.0065	0.4091	0.7519	0.8565
Cover (%)			—— P-value ——			
herbicide	0.0007	0.3380	0.0000	0.0000	0.3891	0.8444
year	0.0000	0.0038	0.0000	0.0000	0.0000	0.0000
herbicide*year	0.2302	0.2485	0.2912	0.3996	0.2083	0.3243
Injury (%)			—— P-value ——			
herbicide	0.0070	0.3380	0.0003	0.0018	0.3887	0.9414
year	0.0000	0.0038	0.0103	0.0000	0.0004	0.1274
herbicide*year	0.5475	0.2485	0.0001	0.0394	0.1396	0.9994

utilizing the macro Turf Analysis 1-2 following methods described by Karcher and Richardson (2005). The software allows for color threshold values of hue and saturation to be adjusted for light intensity and to define the area to be read (Purcell, 2000). Saturation values used ranged from 13-26 with the maximum always set at 100. Hue values used ranged from 47-60 with the maximum always set to 120. Adjustments were made between each data collection date, but not from within each data collection timing.

2.4. Statistical Data Analysis

The statistical data analysis was performmed using R version 3.6.1 [**?**]. Homogeineity of variances of injury, cover and biomass were acessed with *leveneTest* function (package **car**). Gaussean distribution (normality) from biomass data was acessed with *pearson.test* (package *nortest*), *qqnorm* (package **stats**) and *truehist* (package **MASS**) functions. Biomass data was transformed to meet the assumptions of normality with *sqrt* funtion. Generalized linear mixed-effects models function *lmer* (package **lm4**) was fitted to each cover crop species (bruiser annual rye, crimson clover, king annual rye, oat/pea, radish and winter rye) biomass in corn and soybeans; therefore, 12 models were fitted. For each model, herbicide treatments and year were as fixed effects, and replication was random effect. Each cover crop biomass model was subject to analysis of variance (ANOVA) using the *anova* function (package *stats*). For clarity, mean biomass of each treatment are back-transformed using *emmeans* function (package *lmerTest*). Treatment mean and confidence intervals are presented with *emmeans* package (package **emmeans**) at $\alpha = 0.05$.

Assuming non-gaussean distribution, beta distribution with generalized linear mixed-effects models on the Template Model Builder function *glmmTBM* (package **glmmTBM**) was fitted to cover and injury data. To meet assumptions of the model, cover and injury data were transformed to a scale between 0 and 1 but results is presented in the percentage scale. Also, 12 models were generated to injury and cover for each cover crop species presented in corn and soybeans. For each model, herbicide treatments and year were as fixed effects, and replication was random effect. Each cover crop injury or cover model was subject to ANOVA using the *Anova.glmmTBM* function (package **glmmTBM**). Treatment mean and confidence intervals are presented with *emmeans* package (package **emmeans**) at $\alpha = 0.05$.

3. Results

3.1. Weather conditions

May and June of the 2013 growing season received 74 mm more rain and were 2.5 C cooler on average after herbicide application than the same period in 2014. At the time of cover crop

Table 5. Anova soybeans

Anova	Species					
	Bruiser annual rye	Crimson clover	King annual rye	Oat/Pea	Radish	Winter Rye
Biomass (g)			—— P-value ——			
herbicide	0.1071	0.2621	0.9946	0.0197	0.0001	0.1556
year	0.4123	0.0000	0.0216	0.0000	0.0391	0.0000
herbicide*year	0.1631	0.1008	0.9664	0.0171	0.0568	0.4959
Cover (%)			—— P-value ——			
herbicide	0.1051	0.0131	0.0000	0.0000	0.0000	0.0278
year	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
herbicide*year	0.3616	0.8447	0.0000	0.0006	0.0000	0.9279
Injury (%)			—— P-value ——			
herbicide	0.4168	0.9939	0.0002	0.0000	0.0000	0.9938
year	0.3541	0.9909	0.0680	0.0039	0.1356	0.9367
herbicide*year	0.3452	0.9955	0.1050	0.0000	0.0000	0.9998

establishment in 2013, temperature was on average 4 C warmer, and a precipitation event occurred the day after planting.

3.2. Cover Crop Establishment after Corn

In 2013, herbicide residual of *S*-metolachor + mesotrione + glyphosate and flumioxazin + pyroxasulfone reduced biomass by nearly 60% and 36%, respectively, compared to nontreated (2.9 g; Figure 1). However, no biomass reduction was observed in 2014 or bruiser annual ryegrass. Similar trend was observed to Crimson clover, which no herbicide treatment effect was observed in both 2013 (Figure 1) and 2014.

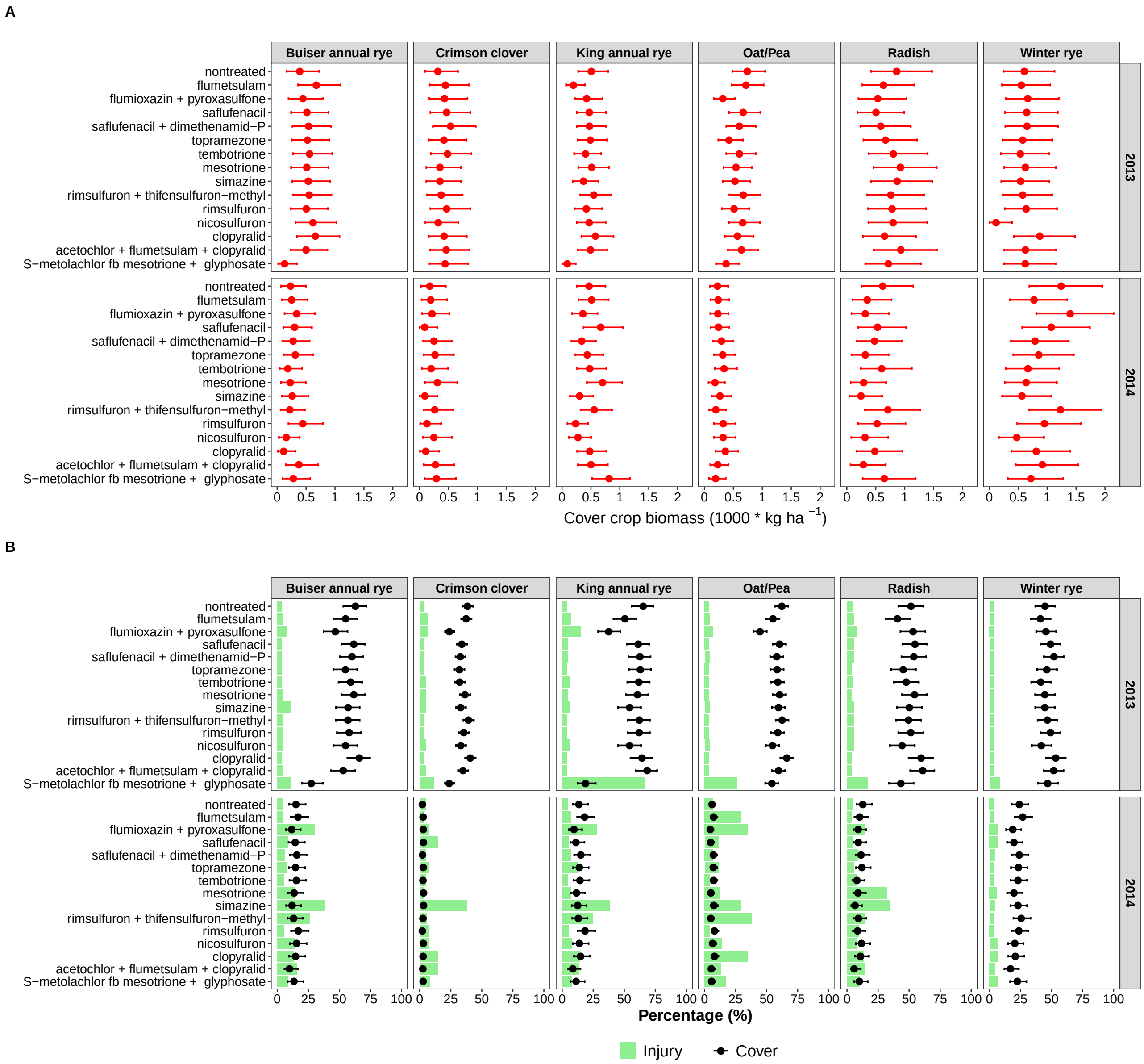
A
B
Buiser annual rye
Crimson clover
King annual rye
Oat/Pea
Radish
Winter rye
2013
2014
nontreated
flumetsulam
flumioxazin + pyroxasulfone
saflufenacil
saflufenacil + dimethenamid−P
topramezone
tembotrione
mesotrione
simazine
rimsulfuron + thifensulfuron−methyl
rimsulfuron
nicosulfuron
clopyralid
acetochlor + flumetsulam + clopyralid
S−metolachlor fb mesotrione + glyphosate
Cover crop biomass (1000 * kg ha −1)
Percentage (%)
Injury
Cover

Figure 1

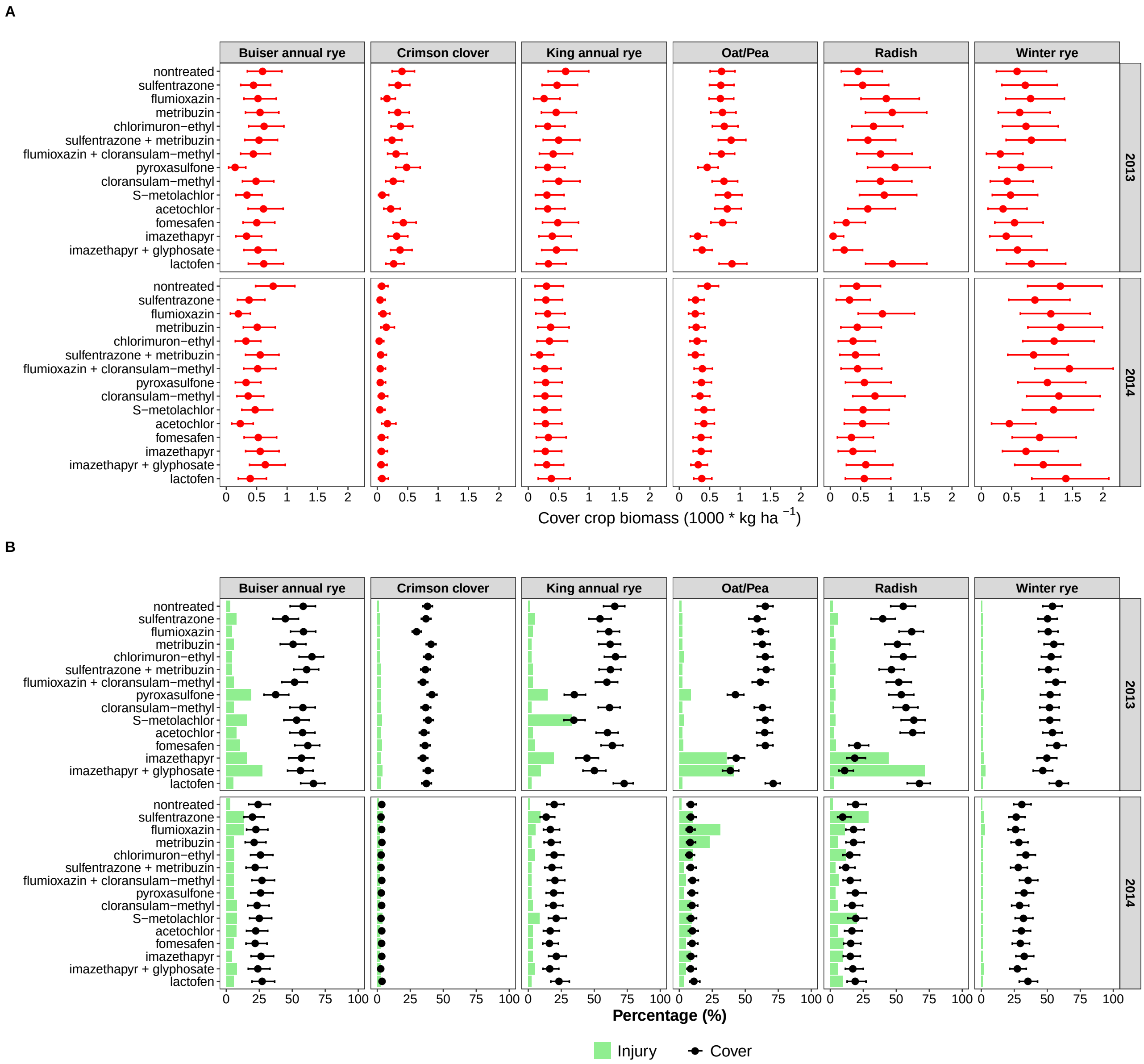
A
Buiser annual rye
Crimson clover
King annual rye
Oat/Pea
Radish
Winter rye
2013
2014
nontreated
sulfentrazone
flumioxazin
metribuzin
chlorimuron−ethyl
sulfentrazone + metribuzin
flumioxazin + cloransulam−methyl
pyroxasulfone
cloransulam−methyl
S−metolachlor
acetochlor
fomesafen
imazethapyr
imazethapyr + glyphosate
lactofen
Cover crop biomass (1000 * kg ha −1)
B
Percentage (%)
Injury
Cover

Figure 2

4. Discussion

Treatments		Species											
		Bruiser annual rye		Crimson clover		King annual rye		Oat/Pea		Radish		Winter rye	
	Timing	2013	2014	2013	2014	2013	2014	2013	2014	2013	2014	2013	1014
		—— Biomass (kg ha-1) ——											
nontreated		393	234	316	178	507	469	741	226	863	620	608	1242
flumetsulan	PRE	678	251	449	193	199	512	719	240	634	354	555	773
flumioxazin + pyroxasulfone	PRE	446	339	433	216	428	362	319	232	535	321	665	1401
saflufenacil	PRE	515	303	468	90	474	670	670	243	506	530	649	1074
saflufenacil + demetenamid-P	PRE	545	276	538	250	475	341	606	296	589	480	654	791
topramezone	EPOST	526	316	422	267	491	438	427	318	670	321	578	858
tembotrione	EPOST	564	188	483	203	410	480	606	342	806	602	538	668
mesotrione	EPOST	512	229	353	308	516	703	547	184	926	291	625	637
simazine	EPOST	538	262	352	93	374	306	529	268	870	246	543	567
rimsulfuron + thifensulfuron-methyl	EPOST	554	219	373	262	552	559	673	199	762	710	579	1233
rinsulfuron	EPOST	505	444	469	128	422	238	513	326	782	523	639	955
nicosulfuron	EPOST	622	160	323	248	471	277	663	324	800	315	118	476
clopyralid	EPOST	622	116	424	110	579	481	574	361	655	484	875	812
acetochlor + flumetsulam + clopyralid	EPOST	501	378	460	275	495	501	642	231	935	287	625	919
S-metolachlor fb mesotrione + glyphosate	PRE fb LPOST	129	283	444	292	94	815	374	196	719	650	622	720
Year		502	260	418	200	419	464	567	263	731	437	577	857
Anova		—— P-value ——											
herbicide		0.9189		0.9218		0.2809		0.3490		0.9082		0.0622	
year		0.0000		0.0000		0.2981		0.0000		0.0000		0.0003	
herbicide*year		0.5099		0.8989		0.0065		0.4091		0.7519		0.8565	

\end{table}

Authors should discuss the results and how they can be interpreted in perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

5. Conclusion

This section is not mandatory, but can be added to the manuscript if the discussion is unusually long or complex.

6. Patents

This section is not mandatory, but may be added if there are patents resulting from the work reported in this manuscript.

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Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "X.X. and Y.Y. conceive and designed the experiments; X.X. performed the experiments; X.X. and Y.Y. analyzed the data; W.W. contributed reagents/materials/analysis tools; Y.Y. wrote the paper." Authorship must be limited to those who have contributed substantially to the work reported.

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Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	Directory of open access journals
TLA	Three letter acronym
LD	linear dichroism

Appendix A

Appendix A.1

The appendix is an optional section that can contain details and data supplemental to the main text. For example, explanations of experimental details that would disrupt the flow of the main text, but nonetheless remain crucial to understanding and reproducing the research shown; figures of replicates for experiments of which representative data is shown in the main text can be added here if brief, or as Supplementary data. Mathematical proofs of results not central to the paper can be added as an appendix.

Appendix B

All appendix sections must be cited in the main text. In the appendixes, Figures, Tables, etc. should be labeled starting with 'A', e.g., Figure A1, Figure A2, etc.

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Sample Availability: Samples of the compounds ...... are available from the authors.