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Katja Koehler-Cole

Sydney Everhart

Yan Gu

Christopher A. Proctor

Margarita Marroquin-Guzman

See next page for additional authors

Authors
Katja Koehler-Cole, Sydney Everhart, Yan Gu, Christopher A. Proctor, Margarita Marroquin-Guzman, Daren Redfearn, and Roger W. Elmore

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RESEARCH LETTER

Is allelopathy from winter cover crops affecting row crops?

Katja Koehler-Cole[1] | Sydney E. Everhart[2] | Yan Gu[3] | Christopher A. Proctor[1] | Margarita Marroquin-Guzman[2] | Daren D. Redfearn[1] | Roger W. Elmore[1]

[1]Dep. of Agronomy and Horticulture, Univ. of Nebraska-Lincoln, 202 Keim Hall, Lincoln, NE 68583-0915, USA

[2]Dep. of Plant Pathology, Univ. of Nebraska-Lincoln, 406 Plant Sciences Hall, Lincoln, NE 68583-0915, USA

[3]Jilin Agricultural Univ., Changchun, Jilin 130118, PR China

Correspondence
Katja Koehler-Cole, Dep. of Agronomy and Horticulture, Univ. of Nebraska-Lincoln, 202 Keim Hall, Lincoln, NE 68583-0915, USA.
Email: kkoehlercole2@unl.edu

Abstract

Cover crops (CC) have been explored in corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), soybean [*Glycine max* (L.) Merr.], and wheat (*Triticum aestivum* L.) systems for their allelopathic potential to control weeds. However, allelopathic compounds may negatively affect these row crops by reducing germination, emergence, and grain yields. We reviewed studies that document allelopathic effects of CC on subsequent row crops in field and laboratory settings. We summarize the influence of CC management, including biomass production, planting and termination timing on allelochemical quantity. Our review found few studies documenting allelopathic effects of CC on row crops in field settings. Studies that focus on understanding yield impacts of CC on row crops should be designed to include allelopathic CC–row crop interactions. Understanding the link between CC management and allelopathic dynamics can help avoid impacts on the growth and productivity of the subsequent row crop.

1 | INTRODUCTION

Allelopathy is one mechanism of plant–soil feedback that uses secondary metabolites to alter soil properties to affect the growth of seedlings (Bennett & Klironomos, 2019). Many cover crops (CC) release allelochemicals; for example, cereal rye (*Secale cereale* L.) and winter wheat (*Triticum aestivum* L.) produce benzoxazinones (BX) (Jabran, Mahajan, Sardana, & Chauhan, 2015; Schulz, Marocco, Tabaglio, Macias, & Molinillo, 2013), hairy vetch (*Vicia villosa* Roth) synthesizes cyanamides (Kamo et al., 2006), and brassicas contain glucosinolates (Kunz, Dj, Varnholt, Walker, & Gerhards, 2016). Allelopathic chemicals from CC have been shown to suppress weed germination and growth under both laboratory and field conditions (Kunz et al., 2016; Rehman et al., 2019; Rice, Cai, & Teasdale, 2012) and were the cause of up to 28% of CC weed suppression, with the remainder being competition (Sturm, Peteinatos, & Gerhards, 2018). The contribution of CC to integrated weed management is increasingly recognized, especially in the face of herbicide-resistant weeds (Osipitan, Dille, Assefa, & Knezevic, 2018).

Row crops following CC sometimes yield less (Martinez-Feria, Dietzel, Liebman, Helmers, & Archontoulis, 2016; Pantoja, Woli, Sawyer, & Barker, 2015) due to N immobilization by the CC (Sievers & Cook, 2018), soil water use by the CC (Holman et al., 2018), and higher incidences of row crop seedling diseases (Acharya et al., 2017). Researchers and farmers often suspect that allelopathic chemicals released from CC may be affecting row crop germination and subsequent growth (Kessavalou & Walters, 1997; Martinez-Feria et al., 2016; Pantoja et al., 2015; Williams, Mortensen, & Doran, 2000). In most cover crop–row crop systems, row crops are planted days to weeks after CC are terminated, and this temporal separation may dilute allelopathic effects as allelochemicals are often short-lived in soil (Rice et al.,

Abbreviations: CC, cover crops; BX, benzoxazinones.

2012). Further, in laboratory studies, allelochemicals were most detrimental to small-seeded species (Liebman & Sundberg, 2006). This may suggest a limited influence of allelopathy on large-seeded row crops such as corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.], but field research investigating these effects is limited.

Cover crop management has evolved as CC adoption has increased. Innovations in CC management could affect their allelopathic impact on row crops. For example, some farmers manage CC to produce high amounts of biomass for weed suppression (Mirsky et al., 2013), interseed CC into row crops at early vegetative stages (Noland et al., 2018), or plant row crops into CC stands before CC termination ("planting green") (Reed, Karsten, Curran, Tooker, & Duiker, 2019). With the increase in CC acreage and management options, it is essential to identify what role allelopathic compounds from CC may play in row crop yield reductions. This information could be used to identify management practices to help growers avoid yield losses from CC without limiting their beneficial characteristics (weed suppression, soil health, etc.). Thus, we conducted a literature review to determine whether there is a clear cause-and-effect relationship of CC allelopathy on row crops. Our research questions were (a) Do CC have allelopathic effects on row crop seed germination and/or yield? and (b) What environmental and management factors influence allelopathic potential of CC?

Core Ideas

- Cover crops (CC) had allelopathic effects on row crop germination in laboratory studies.
- Few studies investigate allelopathic CC–row crop interactions in the field.
- CC had allelopathic effect on row crop in only one field study.
- Increase in CC acreage and evolving CC management justifies greater research efforts.

2 | APPROACH

We conducted a literature review in the fall of 2019 of peer-reviewed journal articles on allelopathic effects of the most common CC—winter annual cereals, brassicas, and legumes—on the most common row crops in the United States: corn, soybean, cotton (*Gossypium hirsutum* L.), and wheat. We aimed to find studies that show a clear cause-and-effect relationship using criteria described by Duke (2015). We included only laboratory studies that either used an aqueous extract from CC, used a known CC allelochemical, or extracted known allelochemicals from CC tissue; we included field studies that measured allelochemicals in the soil and/or CC tissue (Duke, 2015). We used Google Scholar and the search words "Cover Crop* allelopath*" in combination with the search words "corn" or "cotton" or "soybean" or "wheat." We scanned study titles and abstracts and included only those articles that fit the criteria. We used these same keywords to carry out a search on the online site of the journal *Allelopathy*; however, all articles obtained by this search were also found by the Google Scholar search. We scanned the reference section of recent reviews on allelopathic effects of CC to ensure we did not omit important studies. In addition, the authors scanned their own literature collection for papers that could not be found by the online searches. Using these methods, we found seven studies that fulfilled the outlined criteria (Table 1).

3 | RESULTS AND DISCUSSION

3.1 | Allelopathic effects of cover crops on row crops

Inhibitory effects of allelochemicals from winter cereals, brassicas, and legumes on row crops existed in four laboratory studies and one field study (Table 1).

3.1.1 | Corn

Corn germination was sometimes affected by aqueous extracts of winter cereals, brassicas, and legumes. The effect was generally greater for higher concentrations of extracts. Two studies found no or few effects of cereal rye aqueous extracts (Burgos & Talbert, 2000; Dhima, Vasilakoglou, Eleftherohorinos, & Lithourgidis, 2006). Corn root length was also reduced in some studies, more than corn shoot length, probably because roots were in greater contact with the CC extracts (Chovancová, Neugschwandtner, Ebrahimi, & Kaul, 2015). Generally, smaller-seeded plants were more affected than corn, although corn was more susceptible to hairy vetch and cowpea (*Vigna unguiculata* L.) extracts than several other vegetable and weed species tested (Hill, Ngouajio, & Nair, 2006). There were no field studies documenting allelopathic effects of CC in corn using the criteria established.

3.1.2 | Cotton

In a 3-yr field study in semiarid Texas, cotton grown after CC consistently had shorter plant height and lower lint and seed yields, but cotton plant density was not affected. Concentrations of BX compounds in the soil were two to three magnitudes higher under CC than under control plots. Allelopathy

TABLE 1 Summary of studies on allelopathic effects of cover crops on row crops (corn, cotton, soybean, and wheat). All laboratory studies used aqueous extracts of cover crops as allelopathic medium, sometimes in varying concentrations. The field study measured allelopathic compounds in soil after cover crops. Of the measured variables, only variables that were affected by the cover crop are listed

Row crop and cover crop	Site	Variables measured	Effects	References
Corn				
Cereal rye (*Secale cereale* L.)	Laboratory	Germination, root and shoot length	Highest concentrations of aqueous extract reduced root length	Burgos et al., 2000
Cereal rye	Laboratory	Germination, root length, seedling weight	No effects	Dhima et al., 2006
Mustard (*Sinus alba* L.)	Laboratory	Germination, root and shoot length, time to germinate	Highest concentrations reduced germination, root and shoot length	Chovancová et al., 2015
Field bean (*Vicia faba* L.)	Laboratory	Germination, root and shoot length, time to germinate	Higher concentrations reduced germination, root and shoot length, delayed time to germinate	Chovancová et al., 2015
Cowpea (*Vigna unguiculata* L.)	Laboratory	Germination, root length	Higher concentrations reduced germination and root length	Hill et al., 2006
Hairy vetch (*Vicia villosa* Roth)	Laboratory	Germination, root length	Higher concentrations reduced germination and root length	Hill et al., 2006
Red clover (*Trifolium pratense* L.)	Laboratory	Germination, root length	No effects	Liebman & Sundberg, 2006
Cotton				
Cereal rye	Field	Height, density, chlorophyll content, lint and seed yield	Reduced height, lint and seed yield	Li et al., 2013
Wheat (*Triticum aestivum* L.)	Field	Height, density, chlorophyll content, yield	Reduced height, lint and seed yield	Li et al., 2013
Soybean				
Red clover	Laboratory	Germination, root length	No effects	Liebman & Sundberg, 2006
Wheat				
Hairy vetch	Laboratory	Germination, root length	Reduced root length	Geddes et al., 2015
Cereal rye	Laboratory	Germination, root length	Reduced germination, root length	Geddes et al., 2015
Wheat	Laboratory	Germination, root length	Reduced germination, root length	Geddes et al., 2015

is likely to have at least partially caused the observed effects and could have been higher due to low precipitation during the study. However, N immobilization after the cover crop may have occurred as well (Li et al., 2013).

3.1.3 | Soybean

Soybean was not affected by red clover extracts in a laboratory study assessing 44 weed and crop species (Liebman & Sundberg, 2006). We found no laboratory or field studies that investigated allelopathic effects of winter cereals or brassicas on soybean.

3.1.4 | Wheat

A single laboratory study met criteria for inclusion for wheat. Aqueous extracts of winter cereals reduced germination of wheat and radicle elongation of wheat, but aqueous extracts from hairy vetch showed little allelopathic potential. Cyanamide was identified in hairy vetch extracts, but the chemical composition of winter cereals was not evaluated (Geddes, Cavalieri, Daayf, & Gulden, 2015).

Several laboratory studies showed allelopathic effects of CC on row crops, although the four row crops we focused on were typically less affected than other species. Row crops appeared to be most sensitive to allelochemicals during germination, the same time period reported for weed species (Kruidhof, Gallandt, Haramoto, & Bastiaans, 2011). Allelopathic response seems to be dose-dependent; for example, phytotoxin concentration was negatively correlated with radicle and germination inhibition (Hill et al., 2006). However, allelochemical concentrations in laboratory studies do not necessarily represent field conditions. Only one study reported allelopathic compounds, along with crop growth and yields, in the field. This is likely due to the difficulty and expense associated with conducting field experiments to quantify these highly complex relationships. Allelopathy can have similar phenotypic response to interplant competition but must be evaluated separately to demonstrate that CC have allelopathic effects in the field (Duke, 2015).

The lack of reported cause-and-effect relationship does not rule out the occurrence of allelopathic effects of CC on row crops in the field. Research is needed to confirm or negate these relationships, as this is a crucial first step in establishing CC management recommendations to avoid negative impacts from CC. To confirm allelopathic relationships, researchers should follow steps outlined by Duke (2015) by identifying the phytotoxins produced by the CC and determining whether these phytotoxins are found in the soil after CC termination in high enough concentrations to affect row crop development.

3.2 | Factors influencing cover crop allelopathic potential

Environmental factors influence allelopathic potential of CC, either directly by changing the amount of allelochemicals released or indirectly by modifying interactions of allelochemicals with soil and soil microbes. In a laboratory study, aqueous extracts of weeds had greater inhibitory effects on corn radicle elongation when corn was grown in mediums that had greater proportions of sand, compared with mediums with greater proportions of silt and clay. Higher amounts of organic matter and clay particles may bind allelochemicals (Bhowmik & Doll, 1982). Temperature, nutrient, and moisture stress increased the release of allelochemicals from weeds (Einhellig, 1996). Fertilization can lower the amount of allelopathic compounds released but may have no effects if soil fertility is already high (Reberg-Horton et al., 2005). Herbicides applied to the row crop may interact with allelopathic chemicals. Ferulic acid, which is produced by sorghum [*Sorghum bicolor* (L.) Moench], was more toxic in combination with one of the herbicides atrazine, trifluralin, or alachlor (Einhellig, 1996), but whether this occurs with allelochemicals from CC is not known.

The species, cultivar, growth stage, biomass production, and management of CC and subsequent row crops may determine the likelihood of allelopathic effects. An essential question is, Which CC and row crops are antagonistic and should not be grown in sequence? Dicot weed species were more affected by BX compounds from winter cereals than were monocots (La Hovary et al., 2016), but whether this is true for row crops is not clear. In fact, soybean growth and yields were less affected by preceding cereal rye than corn in several studies; however, allelopathic activity was not measured so it is not clear if allelopathy contributed to these effects (Pantoja et al., 2015; Reed et al., 2019). Brassicas' potential for allelopathic weed control was demonstrated in a recent review (Rehman et al., 2019). Residues of brassica and legumes have been shown to inhibit emergence of crop species, including corn (Haramoto et al., 2005, Kruidhof et al., 2011); however, allelochemical compounds were not reported in these studies. Cover crop mixtures of winter cereals, brassicas, and legumes are gaining in popularity. Synergistic and antagonistic allelopathic effects between these species are possible but have received little attention.

Winter cereal cultivars differ in their amount of BX compounds and associated weed suppression (Dhima et al., 2006; Reberg-Horton et al., 2005). Selecting a less allelopathic cultivar may prevent effects on row crops. Cover crop growth stages also influence their allelopathic potential. In cereal rye, BX concentrations and their inhibitory effects on weeds changed over time, peaking before the onset of reproductive growth in March to April (Reberg-Horton et al., 2005). Cover crops are often terminated during that time because they are easier to kill in the vegetative than in the reproductive stages and to ensure timely row crop planting. Selecting an early-maturing cereal rye cultivar or terminating after the onset of the reproductive stage may lower the amount of allelochemicals released by the CC. On the other hand, total BX content (biomass × BX concentration) may increase after the peak BX production if cereal rye accumulates enough biomass to offset lower concentrations. For example, in a North Carolina study, total BX content was highest in a year when rye produced 10 Mg ha^{-1} of biomass (La Hovary et al., 2016). This biomass amount would be unusually high in most row crop systems in temperate zones (Ruis et al., 2019), except in systems where high biomass CC are used for weed suppression (Mirsky et al., 2013).

Allelopathic effects seem to be dose dependent, but allelochemical concentrations needed to inhibit row crop growth under field conditions have not been established. A review of seven laboratory and field studies found that BX concentrations in cereal rye ranged from 177 to 1,981 μg g^{-1} of biomass (Schulz et al., 2013). Total biomass BX content was 5.4 kg ha^{-1} in the above-cited study where rye produced 10 Mg biomass ha^{-1} (La Hovary et al., 2016). Soil concentrations of BX under cereal rye ranged from 27 to 136 ng g^{-1} across years and reduced dry matter of weed species, but it is unclear what amounts would affect row crops. In addition, the persistence of allelochemicals in the soil may depend on the tillage system. Tillage-incorporated cereal rye reached maximum soil BX concentrations sooner and disappeared faster than no-till cereal rye; however, after 2 wk, BX concentrations were usually similar in no-till, tilled, and control plots. Weed species were not affected if planted more than 14 d after rye termination (Rice et al., 2012). Similar time intervals were reported by others (Haramoto et al., 2005; Kruidhof et al., 2011) and demonstrate that a threshold concentration of allelochemicals is required to have a negative effect on row crop development. Temporal overlap between the peak of allelochemical release from a terminated CC and germination of a row crop can be avoided by delaying row crop planting for 2 wk after CC termination. Another option may be to plant the row crop into the living CC and terminate it once the row crop emerges, past its sensitive period of germination. While planting green (planting into a living CC) is becoming more common, reduced corn populations and yields were reported in a Pennsylvania study where cereal rye was terminated within 5 d of corn planting (Reed et al., 2019). More research on this planting method is necessary to investigate how it affects germination and early growth of the row crop.

4 | CONCLUSION

Sustainable cropping systems of the future require rotations that are designed to maximize positive plant–soil feedback (Mariotte et al., 2018), including the use of allelopathic crops for weed control. Unintended negative feedbacks, such as suppressed row crop performance, are sometimes observed, but from our review, it is apparent that much more research is needed to identify cause-and-effect relationships of CC allelochemicals on row-crop growth and development. This research could result in guidelines that will aid farmers in predicting the allelopathic potential of CC given cultivar characteristics and management. Cover crop use is increasing and its management continually evolving, resulting in greater temporal and spatial overlap of CC and row crops that may increase the occurrence of allelopathic inhibition of row crops. From the limited number of studies we found, it appears that row crops are most vulnerable to allelopathic chemicals during germination. The interval between termination of CC and germination of row crops is likely the critical period to mitigate potential allelopathic effects. Several potential methods to avoid temporal overlap, such as terminating CC during later growth stages or delaying row crop planting, have been discussed. However, these methods need to be tested rigorously in the field to establish their effectiveness.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Katja Koehler-Cole
https://orcid.org/0000-0003-4150-6254
Sydney E. Everhart
https://orcid.org/0000-0002-5773-1280
Christopher A. Proctor
https://orcid.org/0000-0003-0291-6103
Margarita Marroquin-Guzman
https://orcid.org/0000-0001-7718-1899
Daren D. Redfearn
https://orcid.org/0000-0003-0295-3131

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