

1 **Short title:** strip till and cover crops affect weed emergence

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4 Spatial and temporal variability in Powell amaranth emergence under strip-tillage 5 with cover crop residue

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13 The objectives of this research were to evaluate temporal and spatial variability in the
14 impact of strip tillage and oat cover crop residue on Powell amaranth emergence, and to
15 determine the role of rainfall in mediating these effects. In field experiments conducted
16 in 2010-2012, Powell amaranth seeds were sown in a fully-factorial combination of two
17 tillage types [strip tillage (ST) vs. full-width tillage (FWT)] and cover crop residue (oats
18 vs. none) at either zero days after tillage (DAT) or 7 to 13 DAT to monitor emergence at
19 two timings. In ST plots, seeds were sown both in the tilled zone ("in-row," IR), and

20 between these tilled zones (“between-row,” BR). In 2011 and 2012, three levels of
21 rainfall were simulated in subplots by either excluding rainfall, allowing natural rainfall,
22 or supplementing rainfall with irrigation. In most cases, ST and oats residue either had
23 no effect or suppressed emergence of Powell amaranth sown at the early planting date.
24 In contrast, the emergence response to ST and residue at the later planting date was
25 generally smaller and more variable, with increases in emergence observed in several
26 cases. Differences between tillage systems in emergence were most pronounced in the
27 BR zone but also occurred IR in some cases, suggesting that inter-zonal effects on
28 biotic or abiotic factors influenced emergence. Oat residue effects—but rarely tillage
29 effects—were often mediated by simulated rainfall, with increases in emergence
30 occurring mostly in dry conditions and decreases occurring more commonly in wetter
31 conditions. These results demonstrate that the suppressive effects of cover crops and
32 ST on weed emergence are inconsistent, temporally and spatially variable, and
33 dependent on complex interactions with factors including rainfall.

34 **Nomenclature:** Powell amaranth, *Amaranthus powelli* S. Wats AMAPO; oats, *Avena*
35 *sativa* L.

36 **Key words:** strip till, zone till, soil moisture, conservation agriculture

37 Conservation agricultural (CA) practices—which are defined by integration of
38 reduced tillage, residue retention, and diverse crop rotations—are frequently promoted
39 for their potential to improve soils, but management of weeds is often a major constraint
40 to their adoption (Hobbs 2007; Kumar et al. 2013; Reicosky 2015). Strip tillage (ST) has
41 garnered interest as a potentially useful component of CA cropping systems involving a
42 wide range of crops including sugar beets (Overstreet 2009), maize (Al-Kaisi et al.
43 2015), wheat (Hossain et al. 2014), and vegetables (Brainard et al. 2013; Luna and
44 Staben 2002). In ST, crops are planted directly into tilled strips while the soil between
45 these strips is left undisturbed. This form of reduced tillage has the potential to reduce
46 erosion, maintain or improve soil quality (Lemke et al. 2012), and reduce input costs
47 through lower fuel and labor use (Luna and Staben 2002) compared to full width tillage
48 (FWT). ST also provides benefits compared to no-till (NT) by facilitating seed bed
49 preparation for sensitive crops like vegetables, and incorporation of soil amendments in
50 the crop root zone. However, weed management in ST systems is often more
51 challenging than under FWT, since primary tillage that disrupts weeds is reduced and
52 residues left on the soil surface can interfere with herbicide or cultivation efficacy (Banks
53 and Robinson 1986; Brainard et al. 2013). These problems are particularly acute in
54 cropping systems for which few herbicide options are available (e.g. vegetables), and
55 for which some form of physical weed management is often required.

56 This study was motivated in part by the lack of available information on spatial
57 and temporal variation in weed emergence response to tillage and cover cropping
58 practices in ST-based CA systems. Although many studies have evaluated the impact
59 of tillage and cover cropping on weed emergence, very few have done so on a scale

60 necessary for understanding the unique behavior of weeds in spatially heterogeneous
61 environments characteristic of ST systems. Understanding how weed emergence
62 differs in distinct zones in ST systems should be helpful for identifying complementary
63 management practices that improve their performance. These are likely to include
64 optimization of weed management practices which target weeds differently in distinct
65 zones within the field, such as zonal cover cropping, combinations of in-row (IR) and
66 high-residue cultivation tools for the between-row (BR) zone, or banded herbicide
67 applications (Brainard et al. 2013, Lowry 2015). In addition, improved understanding of
68 weed emergence patterns in ST may suggest adjustments in the location and timing of
69 zone-specific management practices which influence weed emergence including
70 irrigation (e.g. sub-surface drip) and fertilization (e.g. banded, slow-release fertilizers).

71 Studies evaluating the impacts of tillage on weed emergence often do not control
72 for changes in the distribution of seeds in the soil profile resulting from tillage, and
73 hence provide limited information on the direct effects of tillage-induced changes in
74 edaphic conditions. For example, emergence of Powell amaranth and related species
75 including common waterhemp (*Amaranthus rudis* Sauer) and redroot pigweed
76 (*Amaranthus retroflexus* L.) is sometimes much higher in NT compared to tilled soils
77 (Leon and Owen 2006; Oryokot et al. 1997; Refsell and Hartzler 2009). However, it is
78 unknown the extent to which these differences in emergence were due to greater
79 concentration of seeds near the soil surface under NT or differences in recruitment due
80 to changes in edaphic conditions. In addition to redistributing seeds, tillage can impact
81 weed emergence through a variety of mechanisms including changes in germination
82 stimuli and seed dormancy status. Weed seed germination and hence emergence is

83 typically stimulated by tillage which aerates the soil, releases a flush of inorganic
84 nutrients, creates good seed-soil contact, exposes seeds to light, and alters
85 temperature regimes (Mohler 2001). Tillage effects on predators and decay agents of
86 seeds can also be profound, and further complicate predictions of emergence. For
87 example, reduced tillage systems may provide improved habitats for ground-dwelling
88 seed predators (Shearin et al. 2007), and hence reduce emergence of certain species
89 through increases in rates of predation.

90 Weed seeds in ST fields face very different environments depending on whether
91 they are in the tilled IR zone or the untilled BR between-row zone, and cover crop
92 residues add to this spatial complexity. Under ST, residues are incorporated in the tilled
93 IR zone, but left on the surface as a mulch layer in the untilled BR zone. Emergence is
94 typically decreased by incorporated residues through physical, chemical, and biological
95 means often termed “residue-mediated effects”. For example, incorporating oats
96 reduced weed density by over 90% compared to a tilled soil without cover crop residues
97 (Radicetti et al. 2013). The magnitude of these effects can be variable--incorporated
98 oat residue decreased hairy galinsoga (*Galinsoga ciliata* (Raf.) Blake) emergence by
99 50% in one year, but had no effect in another (Kumar et al. 2009). Surface cover crop
100 residues, such as those located in the BR zone in ST, can also have large impacts on
101 weed emergence (Bernstein et al. 2014; Davis 2010; Mirsky et al. 2011), often larger
102 than those of incorporated residues when these are compared directly (Kruidhof et al.
103 2009). These effects may be driven by changes in abiotic factors including light
104 penetration, physical obstruction, soil temperature, soil moisture, and soil chemical
105 properties (Teasdale and Mohler 1993, 2000). In addition, surface residues may also

106 provide a habitat for agents of decay or predation that contribute to pre-emergence
107 mortality; interactions between light, temperature, and particularly soil moisture may be
108 important regulators of these organisms (e.g. Green 2010; Quinn 2015; Shearin et al.
109 2007).

110 Tillage and cover crop effects on weed emergence and crop yields may be
111 particularly dependent on rainfall patterns. For example, higher soil moisture has been
112 observed in both the IR (Haramoto and Brainard 2012) and BR zones (Dahiya et al.
113 2007) of ST fields relative to similar locations in fields with FWT. This may favor
114 germination and emergence in ST relative to FWT in dry years. Surface cover crop
115 mulches may also increase soil moisture and enhance this effect; emergence of lettuce
116 (*Lactuca sativa* L.) seedlings was greater under a cereal rye (*Secale cereale* L.) mulch
117 than in bare soil in a dry year but lower in normal and wet years (Kruidhof et al. 2009).
118 Based on a meta-analysis of 610 studies comparing no-till based CA practices to FWT,
119 Pittelkow et al. (2015) concluded that crop yield benefits generally required residue, and
120 were dependent on rainfall, with the greatest benefits occurring in dry climates.
121 Although these findings in part reflect improved moisture retention in CA systems,
122 differences in weed emergence response to CA may also have played an important role
123 in some cases.

124 Powell amaranth and its close relatives (e.g. redroot pigweed) are problematic
125 weeds in multiple CA cropping systems throughout the world and are noted for their
126 prolific seed production (Brainard and Bellinder 2004; McLachlan et al. 1995).
127 Worldwide, Powell amaranth has developed resistance to Groups 2, 5, and 7 herbicides
128 (Heap 2016). As such, improved understanding of its response to management

129 practices may help improve the productivity of systems in which it occurs. Previous
130 studies have established the importance of soil temperature and moisture in regulating
131 emergence of Amaranthus species. For example, common waterhemp emergence was
132 delayed in cooler no-till soils (Leon and Owen 2006); Amaranthus seedlings emerged
133 faster in no-till than in tilled soils in a dry year, which the authors attribute to increased
134 soil moisture (Oryokot et al. 1997). Moisture conditions may also influence Powell
135 amaranth through indirect effects on soil nutrient availability or the presence of decay
136 agents. For example, amaranth seedlings are sensitive to damping off pathogens
137 including *Pythium* species (Sealy et al. 1990), which are known to proliferate under
138 moist conditions. Powell amaranth germination is also known to be sensitive to
139 inorganic N concentrations (Brainard et al. 2006) which are strongly influenced by soil
140 moisture and will typically increase in response to tillage events.

141 Weed emergence is the end result of a number of processes including the loss of
142 seed dormancy, germination, and pre-emergence seed and seedling mortality. The
143 main goal of this experiment was to better understand whether processes occurring
144 after dormancy release vary between different zones in ST relative to FWT, and thus
145 how the potential for emerged weeds differs in these zones, both with and without cover
146 crop residues. The specific objectives of this experiment were two-fold: 1) characterize
147 the effects of tillage and cover crop residue on IR and BR emergence of Powell
148 amaranth, and 2) evaluate how rainfall may mediate these effects. We hypothesized
149 that emergence of Powell amaranth would be reduced under ST, and in the presence of
150 oat residue, and that these effects would be most pronounced in the untilled BR zone of
151 strip till. In addition, we hypothesized that both tillage and cover crop effects would be

152 mediated in part by rainfall. In particular, we hypothesized that low rainfall conditions
153 would enhance emergence in ST where a cover crop is present due to moisture
154 conservation, while high rainfall conditions would suppress emergence.

155 **Materials and Methods**

156 **Plot Establishment.** This experiment was conducted in three different sections of a 1.6
157 ha field in 2010, 2011, and 2012 at the Kellogg Biological Station in Hickory Corners, MI
158 (lat 42.4058, lon -85.3845). Soil type at this site consists primarily of an Oshtemo
159 coarse loamy soil series (mixed, mesic Typic Hapludalf) with pockets of Kalamazoo fine
160 loamy soil. Temperature and precipitation data during these three years from a nearby
161 weather station are summarized in Table 1 and Figure 1; this weather station is located
162 approximately 700 m from the experimental site. Prior to use in this experiment, the
163 field was in NT soybeans or NT chemical fallow (prior to the section used in 2012). We
164 examined four treatments—a fully-factorial combination of two tillage levels (ST and
165 FWT) and two cover crop levels (oats or none). These treatments were assigned to
166 main plots that were 3.1 m wide by 4.3 m long.

167 Field operations are summarized in Table 2. The oat cover crop was sown at 93
168 kg ha⁻¹ with a NT drill (John Deere model 750; John Deere Equipment Company;
169 Moline, IL). Glyphosate was applied prior to oat planting in 2011 and 2012, but not in
170 2010 as few emerged weeds were observed in this year. All plots were fertilized in mid-
171 May based on soil nutrient analysis, and typical fertilizer rates for a small grain (2010:
172 19-19-19 provided 43 kg of N, 19 kg of P, and 35 kg of K, respectively, ha⁻¹; 2011: 47 kg
173 N ha⁻¹ with urea; 2012: 10 kg N ha⁻¹ with urea). Weeds were not controlled in the cover

174 crop plots during oat growth; glyphosate application and/or hand weeding was used to
175 control weeds in all plots without oats. Cover crop and weed biomass was sampled
176 prior to burndown glyphosate application in mid-June by clipping all biomass at the soil
177 surface from two 0.25 m² quadrats in each plot. Oats were flail mowed 7 to 12 days
178 after glyphosate application. Due to poor oat growth in 2012, oat residue was raked
179 from areas adjacent to the plots and spread into plot areas to increase biomass to
180 comparable levels to that grown in 2010 and 2011.

181 Additional fertilizer was spread by hand prior to tillage in all plots, with rates
182 based on soil test recommendations for a typical vegetable crop such as cabbage
183 (Warncke et al. 2004). In 2010, 81 kg N ha⁻¹, 100 kg P ha⁻¹, and 69 kg K ha⁻¹ were
184 applied as a combination of monoammonium phosphate, triple super phosphate,
185 potash, and urea. In 2011 and 2012, 78 kg N ha⁻¹, 28 kg P ha⁻¹, and 113 kg K ha⁻¹ were
186 applied as 19-19-19, potash, and urea.

187 Tillage occurred immediately after fertilization. For ST plots, tillage was
188 accomplished with one pass of a two-row strip tiller (Hiniker Model 6000; Hiniker Co.;
189 Mankato, MN), equipped with cutting disks, a shank, berming disks, and a rolling
190 basket. In FWT plots, one pass with a chisel plow was used for primary tillage followed
191 by two passes with a field cultivator for secondary tillage.

192 A small amount of supplemental irrigation was applied in each year over the
193 entire experiment using an overhead system in order to keep soil moisture conditions
194 above the permanent wilting point. A total of 20 mm was applied in 2010, 18 mm in
195 2011, and 52 mm in 2012 (Table 1). In 2012, 38 mm was applied in June prior to tillage

196 and the onset of the emergence trial; the remainder was applied to the entire
197 experiment during the course of the emergence periods.

198 **Weed Emergence Evaluation.** Seeds of Powell amaranth were collected from
199 adjacent fields in the fall preceding each experiment, separated from chaff using a rub
200 board and seed cleaner, and stratified under moist conditions at 4°C for four months to
201 mimic overwintering conditions in the field. Prior to planting the following summer,
202 seeds were soaked overnight in 2 mM gibberellic acid (Buhler and Hoffman 1999) and
203 dried in order to induce greater germination. Following this treatment, Powell amaranth
204 germination rates in petri-dishes at 25°C with a light dark cycle of 14/10 hours were
205 32% and 49% in 2011 and 2012, respectively.

206 Weed seeds were sown either immediately after tillage (0 days after tillage;
207 DAT), or 7 to 13 DAT to simulate those that may emerge at the time when a crop would
208 typically be planted relative to tillage used to incorporate a cover crop. Seeds were
209 sown into 0.09 m² subplot quadrats (0.3 m on each side). In the BR zone of ST, the
210 untilled zone, seeds were sprinkled onto the soil surface and lightly packed. In all tilled
211 zones, seeds were mixed in with the top 5 mm of soil and lightly packed. Separate
212 quadrats were located in each of the IR and BR zones in ST, while only one quadrat
213 was located in each FWT plot (separate quadrats were used for each subplot factor
214 when assessed; see below). All BR quadrats were located in non-tire track areas. The
215 number of Powell amaranth seeds sown in each quadrat was 500 in 2010, 700 in 2011,
216 and 600 in 2012. No attempt was made to separate emergence from the ambient
217 seedbank from total emergence. However, observations of Powell amaranth
218 emergence in adjacent areas without supplemental seeds suggested that emergence

219 from the ambient seedbank represented less than 1% of total emergence in the
220 research plots.

221 We sowed seeds after the tillage events, rather than simulating seed rain prior to
222 tillage or the previous fall. This method of seed placement was chosen in order to
223 better control seed depth and to better track the fate of experimentally-sown seeds.
224 Seeds sown prior to tillage would have been redistributed differently by depth in ST vs.
225 FWT, thereby complicating interpretation. This approach was chosen since our
226 objective was to understand the impact of tillage-induced differences in edaphic
227 factors—not burial depth—on weed emergence. However, it should be noted that
228 seeds stored overwinter and sown following tillage in the spring may have behaved
229 somewhat differently than those overwintering in the field, due to changes in dormancy
230 status or soil-seed contact that may have occurred under field conditions.

231 **Water Manipulation Subplots.** In 2011 and 2012, subplot treatments were included to
232 simulate different rainfall levels. These subplot treatments were applied to separate
233 quadrats (also 0.09 m², 0.3 m on each side) within the main plots and were located at
234 least 0.5 m from each other. One set of quadrats was exposed to ambient moisture
235 conditions (“ambient”—including ambient precipitation and the overhead irrigation
236 applied to the entire site. Additional irrigation water was supplied to another set of
237 quadrats (“+water”) with a backpack sprayer; low pressure (68 kilopascals) was used to
238 avoid washing seeds out of the quadrats. These received the same precipitation and
239 irrigation as ambient treatments, along with an additional 15 mm of water applied in
240 three equal five mm applications over six days. This amount of additional water was
241 chosen to maintain moist soil at the onset of the experiment in 2011 and was

242 maintained for consistency in 2012. Finally, precipitation was excluded from an
243 additional set of quadrats (“-water”) using exclosures (0.6 m x 0.9 m) constructed from
244 plastic sheeting stretched over a flexible plastic frame, with open sides to minimize
245 temperature shifts. The bottom of the frame was in contact with the soil surface, and
246 extended approximately 1.25 cm above the soil surface to avoid lateral movement of
247 surface water into quadrats during rainfall events. Exclosures were placed in the field
248 one hour before rainfall was expected to begin and removed less than one hour after
249 rainfall termination in order to minimize non-moisture related effects (e.g. light,
250 temperature changes). Because precipitation was much higher in 2011 compared to
251 2012 (Figure 1), soil moisture levels in ambient and +water treatments were likely also
252 higher in 2011 compared to 2012, while -water treatments were similar across the two
253 years.

254 **Data Collection.** Emerged seedlings of Powell amaranth were counted and pulled
255 daily until fewer than two seedlings were emerging per quadrat per day for at least three
256 days. Evaluation time periods were as follows: July 5-July 14, 2010 (early) and July
257 14-August 6, 2010 (late); July 4-July 28, 2011 (early) and July 18-August 16, 2011
258 (late); and July 6-August 3, 2012 (early) and July 16-August 3, 2012 (late). Emergence
259 was summed over the entire period. Weeds of other species were removed by hand as
260 they emerged.

261 **Statistical Analysis.** Emergence data were square root transformed as necessary
262 prior to analysis to improve normality. Data were grouped according to their variances
263 when variances were heterogeneous as determined by a Levene’s test; the best model
264 was selected based on Akaike’s Information Criterion. The percentage of emerged

265 seedlings of the total seeds sown was the dependent variable. For both emergence
266 timings, this percentage was subjected to an analysis of variance using SAS PROC
267 MIXED (version 9.2; SAS Institute, Cary, NC). Block (replicate) was considered a
268 random factor. In 2010 when the subplot factors were not tested, a two-way ANOVA
269 was used with tillage, cover crop, and the interaction tested. In 2011 and 2012, tillage,
270 cover crop, and the interaction term were main plot factors, while the subplot treatment
271 (ambient, +water, and -water) was the subplot factor. Emergence was analyzed
272 separately by zone (IR and BR) and by year as initial testing indicated significant zone
273 by treatment and year by treatment interactions. Single degree of freedom contrasts
274 and slicing were used to separate significant interactions where appropriate; $\alpha=0.05$
275 was selected as the significance level.

276 **Results and Discussion**

277 **Weather Conditions.** During the period of cover crop growth (mid-April to late June),
278 2010 was relatively warm and wet compared to the ten-year average (Table 1). April
279 2011 was 1.8°C cooler than the ten-year average and also wetter. Spring 2012 was
280 warmer and much drier than average which negatively impacted cover crop growth,
281 resulting in lower oats biomass accumulated in 2012 (Table 3).

282 Average daily temperature during the duration of the emergence periods is
283 shown in Figure 1, as is daily precipitation (plus whole-experiment irrigation when
284 applied) and volumetric soil moisture measured at 10 cm depth under sod at the nearby
285 weather station. As such, soil moisture levels presented in Figure 1 reflect only

286 precipitation (not supplemental irrigation) and are provided only to illustrate relative
287 differences in baseline precipitation and soil moisture conditions between years.

288 In 2010, ambient soil moisture was initially high but decreased throughout the
289 emergence period of early planted seeds, remaining relatively low during the period of
290 peak emergence represented by the thicker horizontal line (Figure 1A). In 2011,
291 ambient soil moisture was initially low during the emergence period of early planted
292 seeds, but increased due to a large precipitation event on July 12, prior to peak
293 emergence during this period (Figure 1B). Finally, soil moisture remained low
294 throughout both emergence periods in 2012 (Figure 1C). During the emergence of late
295 planted seeds, soil moisture was initially low in 2010, including during the time of peak
296 emergence, and increased after rainfall events starting on July 21. Ambient soil
297 moisture was initially higher during the emergence of late planted seeds in 2011, but
298 decreased steadily.

299 **Cover Crop and Weed Biomass.** Oats produced approximately 2800 kg ha^{-1} in 2010
300 and 2011 (Table 3). Oat growth was poor in 2012, likely because of low precipitation
301 during May and June 2012 (Table 1), producing on average only 1900 kg ha^{-1} . With the
302 residue raked into the plot areas, biomass was increased to almost 2800 kg ha^{-1} . Weed
303 biomass within the oat cover crop was variable and ranged from 108 to 1084 kg ha^{-1} . Higher
304 weed biomass was observed in 2010, the year in which we did not apply
305 glyphosate prior to cover crop planting. Lower weed biomass was observed in 2011,
306 the year with higher than average rainfall, suggesting that oats are more successful in
307 out-competing weeds in years with adequate moisture (Ateh and Doll 1996). Dominant
308 weed species within the cover crop growth period were shepherd's purse (*Capsella*

309 *bursa-pastoris* (L.) Medik), mouse-ear cress (*Arabidopsis thaliana* (L.) Heynh), and
310 common chickweed (*Stellaria media* L.).

311 **Tillage Effects on Emergence Following Early Planting.**

312 *In-row (IR)*. At the early timing (planted 0 DAT), emergence of Powell amaranth was
313 lower in the tilled IR zone of ST compared to FWT in two of three years—by 42% and
314 23%, respectively, in 2010 and 2012 (Table 4; Figure 2A). IR emergence did not differ
315 between tillage types in 2011. We did not observe any interactions between tillage and
316 the moisture subplots in this zone (Table 4), so this suppression does not appear to be
317 related to differences in soil moisture. Other factors that may have influenced Powell
318 amaranth emergence include physical differences in the seedbed, temperature, or
319 impacts on nitrogen or fungal pathogens. Others have demonstrated lower soil
320 temperatures (Mochizuki et al. 2007) and lower availability of N (Haramoto and Brainard
321 2012) in the IR zone of ST, both of which could reduce germination and emergence of
322 Powell amaranth (Brainard et al. 2006).

323 *Between-row (BR)*. Compared to FWT, emergence of Powell amaranth at this first
324 planting time was reduced by 62% in ST-BR in 2010 and by 72% in ST-BR in 2011 but
325 only with oats (Figure 2B). The effects of oats and ST on emergence in 2011 did not
326 depend on moisture (no significant interactions; Table 4), so this suggests that
327 emergence was suppressed in this zone due to another mechanism—perhaps due to
328 physical impedance from the surface oats residue.

329 In 2012, tillage had very different effects on emergence—ST often increased BR
330 emergence relative to FWT but these effects depended on both moisture treatments

331 and oats residue. In particular, emergence was greater in ST-BR relative to FWT only
332 in +water subplots and ambient moisture subplots with oats (Figure 2C). This result
333 was contrary to the hypothesis that higher emergence would occur in low moisture
334 treatments in the ST-BR zone in dry years like 2012 (Table 2; Figure 1C) because of the
335 moisture-conserving effects of ST.

336 In 2012, Powell amaranth emergence in +water subplots was lower than
337 emergence in ambient and –water subplots for all combinations of tillage and oats
338 residue except ST oats (Figure 2C). Since higher soil moisture generally stimulates
339 germination (Oryokot et al. 1997), a possible explanation of this counterintuitive result is
340 that soil moisture added to the +water subplots through irrigation increased post-
341 germination mortality prior to seedling emergence. Additional water that we applied
342 evaporated quickly in this extremely hot and dry year (Figure 1C). It is possible that
343 moisture persisted long enough for seeds to imbibe and even to commence the
344 germination process, but that moisture was insufficient for complete germination and
345 emergence, especially in FWT treatments. Emergence of small Amaranthus seedlings
346 is susceptible to soil crusting in loamy soils (Bavec and Mlakar 2002); we observed soil
347 crusting to a greater extent in the +water subplots in FWT and ST-IR, which may have
348 further inhibited successful emergence.

349 Overall, it is not surprising that we generally observed stronger effects of ST
350 relative to FWT in the untilled BR zone compared to tilled IR zone (Figure 2), and that
351 there were more interactions with the cover crop in the BR zone as this remains as a
352 surface mulch layer in this zone in ST (Table 4). However, our rainfall subplot

353 treatments provided little support for the hypothesis that these tillage effects were
354 mediated by soil moisture.

355 **Oat Cover Crop Effects on Emergence Following Early Planting.**

356 *In-row (IR).* In 2011, oats stimulated emergence of Powell amaranth, but only in the –
357 water treatment (Figure 3A). This is consistent with our original hypothesis that the
358 incorporated oats residue may have increased emergence by relieving some of the
359 moisture limitation in the dry conditions maintained under our precipitation exclosures.
360 In 2012, in contrast, oats suppressed emergence of Powell amaranth, but only under
361 ambient and +water treatments. Moisture additions in this very dry year may have
362 contributed to post-germination, pre-emergence seedling mortality through soil crusting
363 or pathogen stimulation.

364 *Between-row (BR).* In all years, emergence of early planted Powell amaranth was
365 either reduced or unaffected by oats compared to no oats (Table 4). In 2010, oats
366 reduced emergence of early planted BR Powell amaranth by 53% (Figure 3B). In 2011,
367 oats reduced emergence of early planted BR Powell amaranth by 60%, but only in ST-
368 BR where the oats residue remained on the soil surface (Figure 3B). Oats residue only
369 reduced emergence in some of the FWT subplot treatments in 2012 (see Figure 2C).
370 Specifically, oats reduced emergence in ambient subplots (effects slicing $p=0.008$; $F (1,$
371 $55)= 7.52$) and in +water subplots (effects slicing $p=0.040$; $F (1,55) = 4.45$).

372 The effects of oats residue on Powell amaranth emergence in the BR zone were
373 also mediated by moisture subplots in both 2011 and 2012 (Table 4). In 2011, across
374 both tillage types, oats suppressed emergence of Powell amaranth only in ambient and

375 +water treatments (Figure 3B). One explanation for this result is that the combination of
376 oats residue and high soil moisture stimulated fungal pathogens such as *Pythium* and
377 *Fusarium*, which contribute to post-germination pre-emergence mortality (see Mohler et
378 al. 2012). This hypothesis is also consistent with suppressive effects of oats on
379 emergence in 2010, when initial soil moisture conditions were high (Figure 1A).

380 As in the IR zone, Powell amaranth emergence in 2011 without oats (Figure 3B)
381 was lowest where water was withheld (effects slicing $p=0.0003$; $F(2, 56)=9.43$), but
382 emergence with the oats residue was similar regardless of the moisture manipulation
383 (effects slicing $p=0.17$; $F(2,56)=1.86$). In 2012, oats also reduced emergence under
384 ambient and +water treatments, but this effect was only observed under FWT (Figure
385 2C). Again, we suspect that increased post-germination mortality may have been due
386 to soil crusting. While surface oat residue was expected to increase soil moisture,
387 potentially stimulative moisture effects may have been masked by suppressive effects
388 of these residues—blocking light, reducing soil temperature, and otherwise physically or
389 biologically impeding seedling emergence.

390 Reductions in BR emergence in ST with oats, observed in 2011, are consistent
391 with multiple studies that demonstrate lower emergence under cover crop residue
392 mulches (Bernstein et al. 2014; Campiglia et al. 2012; De Bruin et al. 2005; Nord et al.
393 2011; Radicetti et al. 2013; Smith et al. 2011). However, several studies have noted
394 that this effect can be inconsistent, especially with low cover crop biomass production
395 (e.g. $<4000 \text{ kg ha}^{-1}$; De Bruin et al. 2005), and later in the season (Mirsky et al. 2011).
396 Oats biomass in our study was less than 3000 kg ha^{-1} in all years (Table 3), which could

397 explain why we did not consistently observe lower emergence in the BR zone of ST with
398 oats.

399 **Tillage Effects on Emergence Following Late Planting.**

400 In 2010, ST increased emergence of Powell amaranth by 72% IR and by 81% BR
401 relative to FWT but only with oats (Figure 4). In contrast, in 2011, ST resulted in lower
402 Powell amaranth emergence relative to FWT in both zones (Figure 4). Manipulating
403 moisture additions did not affect this tillage response in 2011 (Table 5; tillage by
404 moisture interaction NS) suggesting that factors other than moisture were responsible
405 for the suppression of emergence in ST in 2011. In 2010, moisture subplots were not
406 studied, but ambient conditions during late emergence were dry (Figure 1A), so it is
407 possible that observed stimulative effects of ST that year were due to greater moisture
408 retention. However, this hypothesis was not supported by results in 2012, which had
409 comparably dry ambient moisture conditions (Figure 1C).

410 **Oat Cover Crop Effects on Late Emergence.**

411 *In-row (IR).* In 2010, oats increased emergence of IR Powell amaranth but only in ST
412 (Figure 5A). There was no effect of oats residue in 2011 (Table 5). In 2012, oats
413 reduced emergence of the late planted IR seeds by approximately one-third in ambient
414 moisture and +water subplots (Figure 5A). This is similar to the effect observed at the
415 early timing, when oats also reduced emergence in these subplots (Figure 3A).

416 *Between-row (BR).* Oats residue increased emergence of late planted Powell amaranth
417 in ST-BR almost three-fold relative to no oats in 2010, but no differences were observed
418 in 2011 or 2012 (Table 5; Figure 5B). This increased emergence with oats at the late

419 timing contrasts sharply with the inhibitory effect of oats observed at the early timing
420 (Figure 3B). Interestingly, soil moisture conditions also contrasted sharply between
421 early and late timings in 2010, with wet conditions prevailing for the first week at the
422 early timing, and dry conditions occurring during the period of peak emergence at the
423 late timing (Figure 1A). While these results from 2010 are consistent with the
424 hypothesis that oats suppressive effects are most pronounced under moist conditions,
425 they were not observed consistently.

426 **Conclusions**

427 In the majority of cases examined, strip tillage and oats residue either had no
428 effect, or suppressed emergence of Powell amaranth seeds placed near the soil surface
429 immediately after tillage (Figures 2 and 3). These effects were often large—e.g. up to
430 72% reduction in emergence in BR-ST with oats compared to FWT with oats in one
431 year (Figure 2B)—though variable. Assuming that the density of non-dormant Powell
432 amaranth seeds in the germination zone is similar in the two tillage types, our results
433 suggest that growers utilizing ST with cover crops would see lower emergence
434 immediately after tillage relative to a field in FWT. However, when seeds were sown 7
435 to 13 days after tillage, emergence responses to ST and oats were generally smaller
436 and more variable, with increases in emergence noted in several cases. This finding
437 highlights that growers are not likely to see season-long weed suppression from ST with
438 a spring planted oat cover crop, and that late season weed emergence may sometimes
439 be greater in ST compared to FWT.

440 Overall, our results demonstrated large variability in Powell amaranth
441 emergence between years and zones in response to tillage and cover cropping, even
442 when controlling for seed burial depth and dormancy status. For example, on a field
443 scale and summed across both zones, the emergence of sown Powell amaranth seeds
444 in 2010 was 50% lower in ST compared to FWT regardless of whether a cover crop was
445 used. In the next year, however, Powell amaranth emergence was 44% lower in ST
446 compared to FWT with oat cover crop residue, but only 17% lower without that residue.
447 In a very dry year like 2012, the results were more complicated: in ambient moisture
448 conditions emergence was similar in ST and FWT without a cover crop, while ST
449 resulted in an 84% increase in emergence relative to FWT if an oat cover crop was
450 used.

451 The relationship between Powell amaranth emergence observed in our study and
452 that which would actually be experienced by a grower adopting CA practices depends
453 on several important factors not evaluated in our study including tillage-induced impacts
454 on the vertical distribution of seeds in the soil, seed dormancy status, seed predation,
455 and seed rain. Our method of placing seeds with the same dormancy status near the
456 soil surface after tillage facilitates better understanding of the impact of edaphic
457 conditions on emergence (independent of seed depth and dormancy status), but limits
458 our ability to predict the overall weed emergence response governed by these multiple
459 factors. Among these factors, tillage effects on vertical distribution of seeds in the soil is
460 particularly important: since reduced tillage practices including ST generally result in a
461 shallower distribution of seeds near the soil surface over time (e.g. Cardina et al. 1991),
462 the suppressive effects of ST that we observed might be offset by greater seed density

463 in the germination zone. Clearly, improved predictions of weed emergence in response
464 to tillage and cover cropping depends on integration of emergence responses like those
465 examined in this study with population dynamic models which account for other
466 important factors influencing weed emergence.

467 Our hypothesis that variation in emergence response to tillage and cover
468 cropping could be explained in part by rainfall conditions was not consistently supported
469 by our results. In some cases, emergence of Powell amaranth in response to tillage
470 and cover crops was unaffected by simulated rainfall manipulations, suggesting that
471 other mechanisms such as changes in soil physical conditions (e.g. surface crusting),
472 fungal pathogens, allelopathy, or temperature effects were more important. However, in
473 several cases, particularly for oat-induced effects on emergence, rainfall/irrigation
474 appeared to play an important role. In particular, oats residue increased emergence
475 most often in dry conditions while emergence was suppressed most commonly in wetter
476 conditions.

477 While some generalizations about the emergence response can be made, the
478 observed variability in our study highlights two key points: 1) more complex
479 conservation agricultural systems are likely to result in more variable and complex
480 responses by the weed community than FWT practices, and 2) further research is
481 needed to elucidate mechanisms responsible for this variability. Because our results
482 demonstrated strong spatial and temporal variability in emergence responses,
483 development of management practices targeting distinct zones and timings (e.g. zonal
484 cover cropping, in-row cultivation tools or slow-release banded fertilization) will likely be
485 particularly helpful for overcoming weed management constraints in these systems.

486

487

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617 and the physical properties of mulches. *Weed Sci* 48:385-392

- 618 Warncke D, Dahl J, Zandstra B (2004) Nutrient recommendations for Michigan
619 vegetable crops. Michigan State University Extension Bulletin Publication E2934

620 Table 1. Monthly average temperature and monthly total precipitation (plus overhead
 621 irrigation applied to the entire experiment) for April to August in 2010, 2011, and 2012 at
 622 the Kellogg Biological Station in Hickory Corners, MI. Ten-year average monthly
 623 temperature and average total monthly precipitation from 2002-2011 is also provided.

	Average temperature (°C)				Total precipitation and irrigation (in parentheses) (mm)			
	10 year average				10 year			
	2010	2011	2012	¹	2010	2011	2012	average
April	11.9	7.6	8.8	9.4	71	246	109	73
May	16.1	15.1	17.2	14.4	135	142	30	112
June	20.2	20.2	21.0	20.1	184	47	23	85
July	23.5	24.1	25.3	22.1	149	187 ³	45	94
August	22.5	20.7	20.7	21.0	34 (20)	96	70	101

624 ¹ 2002-2011

625 ² Irrigation applied in June 2012 was applied prior to sowing the experimental seeds.

626 ³ rainfall in July 2011 was scattered, with 59 mm falling prior to July 6 and 117 mm
 627 falling within 3 days (July 27-29). Overhead irrigation was added to the entire
 628 experiment on July 15 and 19 when needed (by visual estimation) by a nearby cabbage
 629 crop.

630 Table 2. Timeline for field operations in 2010-2012.

Operation	2010	2011	2012
Glyphosate application	--	4/13	4/6
Oat cover crop established	4/20	4/13	4/18
Oat and weed biomass measured	6/17	6/16	6/20
Cover crop terminated with glyphosate	6/17	6/17	6/22
Residue flail mowed	6/29	6/24	6/29
Fertilizer applied, plots tilled, first set of seeds planted	7/1	6/30	7/3
Second set of seeds planted	7/8	7/13	7/11
	(7 DAT ¹)	(13 DAT)	(8 DAT)

631 ¹DAT=days after tillage

632 Table 3. Average cover crop and weed biomass prior to termination (standard error in
633 parentheses). Biomass was collected from two 0.25 m² quadrats per plot.

	Dry biomass		
	2010	2011	2012
-----kg ha ⁻¹ -----			
Oats	2728 (380)	2812 (208)	2752 ¹ (552)
Weeds	1084 (312)	108 (28)	392 (196)

634 ¹ includes supplemental residue raked into plot areas

635 Table 4. Results of a three-way ANOVA for early in row (IR) and between row (BR) emergence of Powell amaranth
636 beginning 0 days after tillage. Main plot factors were tillage and cover crop, with moisture treatment (ambient, +water, -
637 water) as the subplot factor.

Factor	IR			BR		
	2010	2011	2012	2010	2011	2012
Tillage (T)	0.014	0.123	0.024	0.001	<0.0001	<0.0001
Cover (C)	0.259	0.103	0.013	0.028	0.049	0.057
T*C	0.146	0.677	0.190	0.150	0.002	0.166
Moisture (M)	--	0.508	<0.0001	--	0.039	<0.0001
T*M	--	0.847	0.523	--	0.771	0.001
C*M	--	0.047	0.043	--	0.001	0.987
T*C*M	--	0.696	0.536	--	0.711	0.011

638

639 Table 5. Results of a three-way ANOVA for late in row (IR) and between row (BR) emergence of Powell amaranth
640 (AMAPO) beginning 7 to 13 days after tillage. Main plot factors were tillage and cover crop with moisture treatment
641 (ambient, +water, and -water) as the subplot factor.

Factor	IR			BR		
	2010	2011	2012	2010	2011	2012
Tillage (T)	0.113	0.025	0.822	0.007	0.078	0.601
Cover (C)	0.195	0.578	0.079	0.015	0.219	0.304
T*C	0.005	0.810	0.836	0.001	0.323	0.211
Moisture (M)	-	0.019	<0.0001	-	0.006	<0.0001
T*M	-	0.725	0.410	-	0.821	0.145
C*M	-	0.479	0.009	-	0.232	0.243
T*C*M	-	0.727	0.882	-	0.167	0.533

642

643 **List of Figure legends**

644 Figure 1. Air temperature, volumetric soil moisture, and precipitation + irrigation in 2010
645 (A), 2011 (B), and 2012 (C). Soil moisture levels reflect only precipitation (not
646 supplemental irrigation) and are provided only to illustrate relative differences in
647 baseline precipitation and soil moisture conditions between years. The periods during
648 which emerged weeds were counted are denoted by horizontal black lines; periods of
649 peak emergence are shown with a thicker line.

650 Figure 2. Effects of tillage on emergence of Powell amaranth planted early (sown zero
651 days after tillage) in row (IR) (A) and between row (BR) (B), and a three-way interaction
652 on BR emergence in 2012 (C). Error bars represent +/- 1 standard error (SE). Within
653 each year or interaction, significance levels for the difference between full-width tillage
654 (FWT) and strip till (ST) are shown. NS=difference is not significant; * p<0.05; **
655 p<0.01; *** p< 0.001.

656 Figure 3. Effects of oat cover crop on emergence of Powell amaranth planted early
657 (sown zero days after tillage) in row (IR) (A) and between row (BR) (B). Error bars
658 represent +/- 1 standard error (SE). Within each year or interaction, significance levels
659 for the difference between oats and no oats are shown. T=tillage, C=cover crop,
660 M=moisture; these denote significant interactions between the experimental factors.
661 NS=difference is not significant; * p<0.05; ** p<0.01; *** p< 0.001.

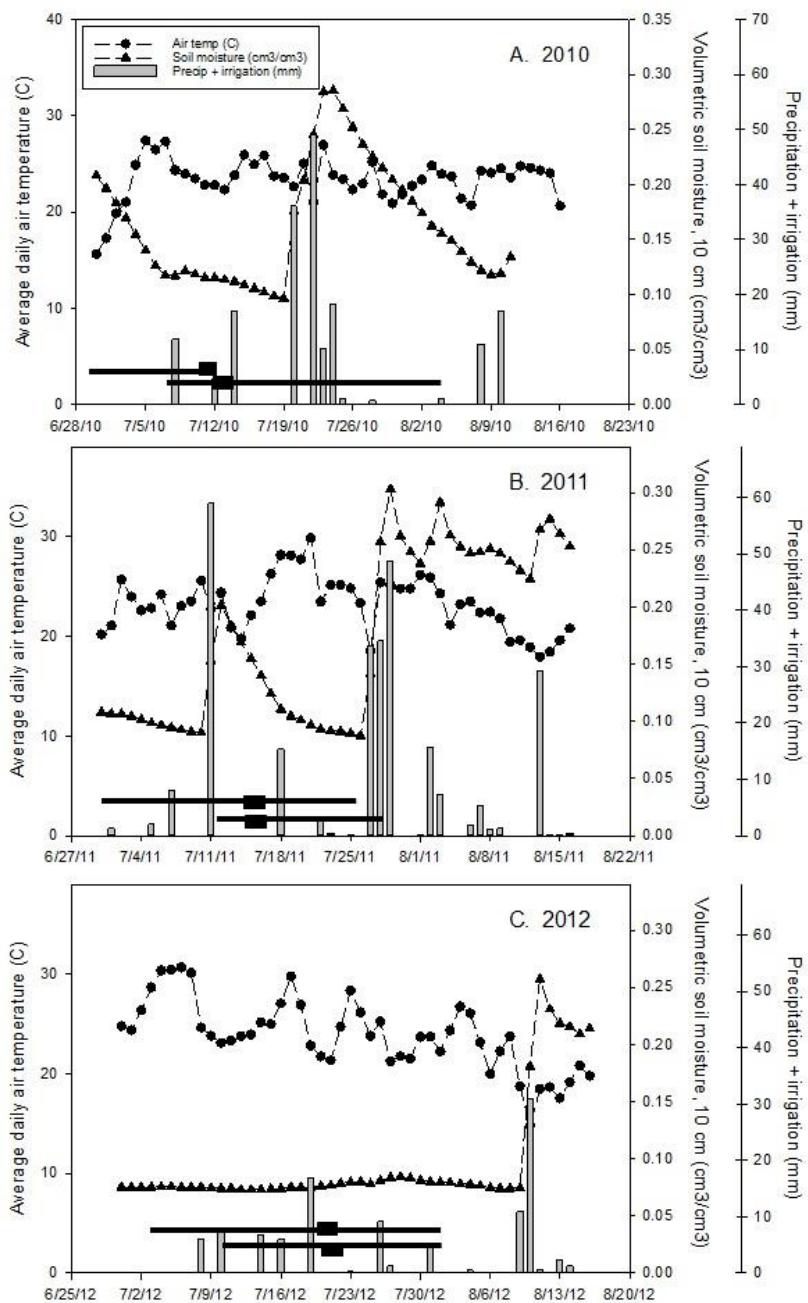
662 Figure 4. Effect of tillage on emergence of Powell amaranth planted later (sown 7-13
663 days after tillage) in row (IR) (A) and between row (BR) (B). Error bars represent +/- 1
664 standard error (SE). Within each year or interaction, significance levels for the

665 difference between full-width tillage (FWT) and strip tillage (ST) are shown.

666 NS=difference is not significant; † p<0.10; * p<0.05; ** p<0.01; *** p< 0.001.

667 Figure 5. Effect of oat cover crop on emergence of Powell amaranth planted later
668 (sown 7 to 13 days after tillage) in row (IR) (A) and BR (B). Error bars represent +/- 1
669 standard error (SE). Within each year or interaction, significance levels for the
670 difference between oats and no oats. NS=difference is not significant; * p<0.05; **
671 p<0.01; *** p< 0.001.

Figure 1



673 Figure 2

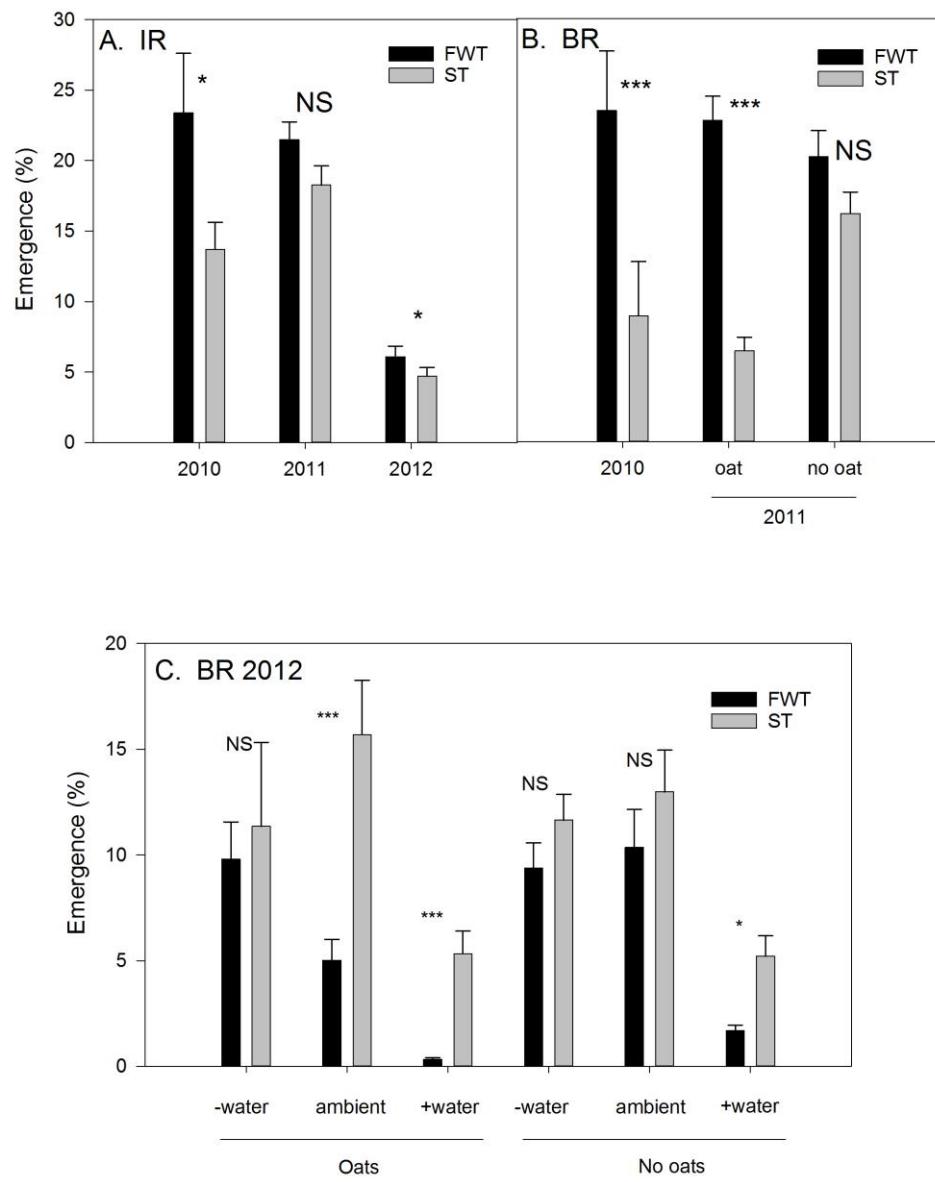


Figure 3

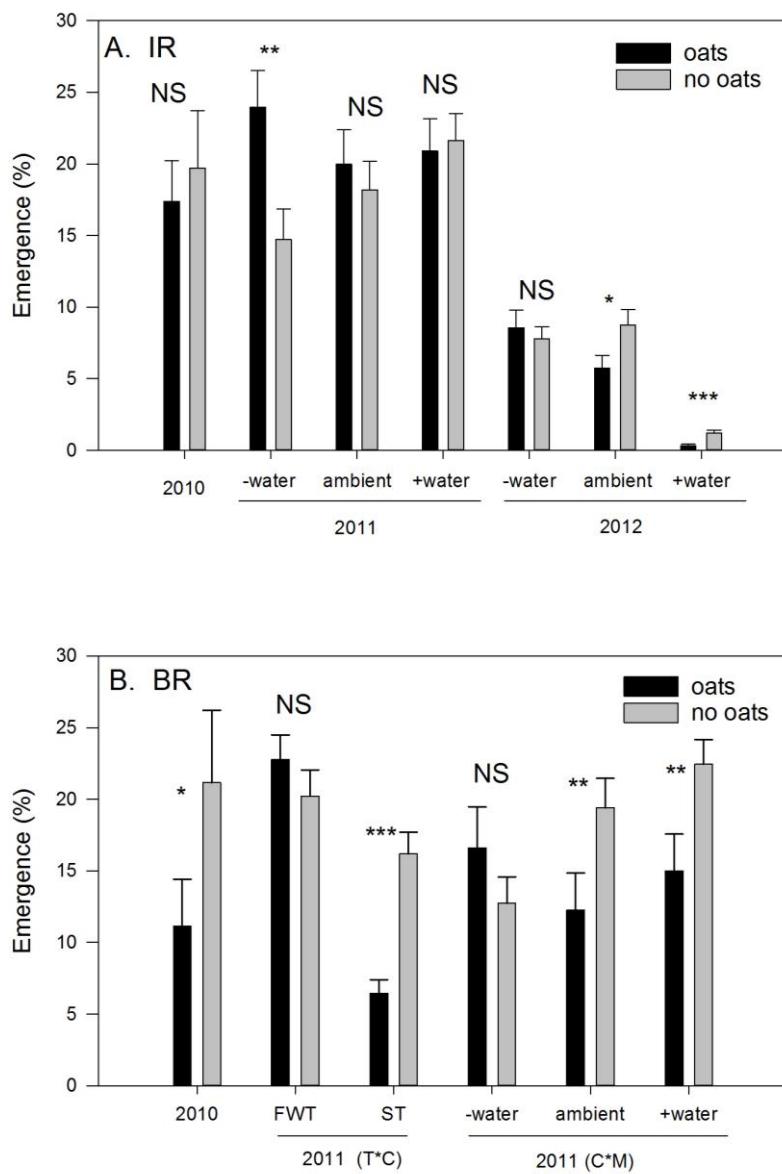


Figure 4

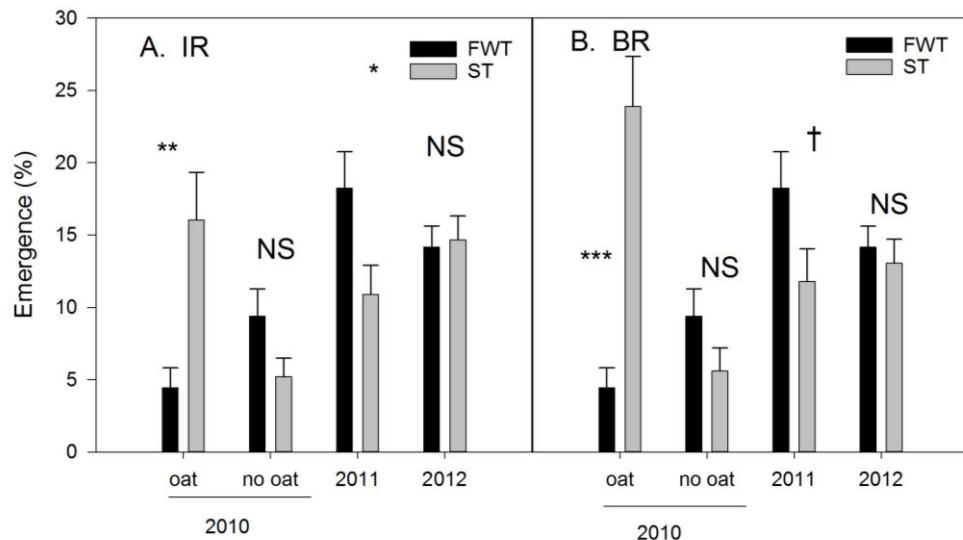


Figure 5

