Australian Journal of
Crop Science

AJCS

AJCS 10(9):1312-1318 (2016) ISSN:1835-2707
DOI: 10.21475/ajcs.2016.10.09.p7799

The effects of nitrogen and neighbouring crops on maturation and timing of seed dispersal in *Hordeum spontaneum* Koch. and *Brassica kaber* (DC.)

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Abstract

Reproductive development and then timing of seed dispersal in many weeds is positively correlated with intensity/availability of environmental resources. In this study, we investigated the effects of nitrogen availability and the type of the crop on timing of weed seed dispersal. Two agricultural weeds; wild barley *(Hordeum spontaneum* Koch.) and wild mustard (*Brassica kaber* (DC.)) were grown in wheat and oilseed rape crops under a range of nitrogen levels. *H. spontaneum* seeds that developed under no or low nitrogen levels (0 and 60 kg ha^{-1}) reached their final maturation stage sooner than those that developed under high nitrogen levels (120 and 240 kg ha^{-1}), resulting in an earlier seed dispersal (109 and 76 degree-days where grown in wheat and oilseed rape cropping systems, correspondingly). In all nitrogen levels, *H. spontaneum* seeds developed in wheat crop reached their maturation stage sooner, and were then dispersed sooner than those developed in oilseed rape cropping system. The results of this study could help growers to make the best decision on weed management through management of seed dispersal. High nitrogen application, for example, with an early harvest may mean that a significant proportion of seeds are taken up to the combine harvester traveling long distances as grain impurity. In contrast, low nitrogen application with a late harvest may result in the majority of seeds falling to the ground and increasing subsequent crop interference. Therefore, an infested crop should be harvested as early as possible to reduce the quantity of weed seeds entering the seed bank.

Keywords: oilseed rape, seed maturation, wheat, wild barley, wild mustard.

Introduction

Seed dispersal, in an applied context, enables agricultural weeds to colonize unoccupied sites within or outside a field. Plant traits enhancing dispersal thus contribute to weediness (Baker 1974; Barnaud et al., 2013; Marco et al., 2002; Tilman, 1997; Vilà and D'Antonio, 1998). If all seeds descend immediately around their parent plant, then the weed has little ability to invade new areas or to expand its range (Cousens and Mortimer, 1995; Cousens et al., 2008a; Cousens et al., 2008b). Species whose seeds contaminate grain are thus able to become widespread. Agricultural weeds are often patchily distributed within a field (Cousens and Mortimer, 1995) and local dispersal around the parent results in patches that persist over many years (Wilson and Brain, 1991). With increasing interest in ecological weed management and site-specific management, research is currently developing tactics and technologies to spray only dense patches of weeds ("patch spraying") and to leave other areas unsprayed (Andújar et al., 2011; Armstrong et al., 2007; Brown and Noble, 2005). The ability to predict the distribution of weeds could aid decisions on the spraying of weed patches, particularly where pre-emergence herbicides are to be used (Oriade et al., 1996; Paice et al., 1998). To evaluate this method of weed management, we need more information on weed demographic data in both spatial and temporal context. Likewise, improving harvest methods for collection of weed seeds in order to reduce the use of herbicides and to manage herbicide resistance have been widely investigated (Goplen et al., 2016; Schwartz et al., 2016; Shirtliffe and Entz, 2005; Walsh et al., 2013; Walsh and Powles, 2014). Therefore, the determination of those factors that affect the proportion of weed seeds that are dispersed before and after harvesting the crop is fundamental to the successful development of novel ways for removing weed seeds from the field. During growth and development, seeds must be connected securely to the parent plant by tissues which supply them with resources. Eventually, nonetheless, seeds leave their parents through dispersal. An abscission layer usually forms between the maternal tissue and seeds, providing a line of weakness at which the seed can separate (Taghizadeh et al., 2009). Although the act of dispersal begins with the departure of the propagule from the parent plant, many factors contributing to the dispersal trajectory occur very much earlier than this moment (Cousens et al., 2008a; Cousens et al., 2008b; Kelly et al., 2013; Taghizadeh et al., 2012). These are characterised as: plant growth and development, phenology of the parent plant, resource availability; and maternal plant environment.

The environmental conditions during the final stage of fruit/seed maturation and release can significantly affect dispersal distances (Kuparinen, 2006; Nathan, 2006; Soons and Bullock, 2008), directionality (Greene et al., 2008; Savage et al., 2010; Wright et al., 2008) and the probability of reaching favourable site conditions for germination (Cousens et al., 2008a; Nathan and Muller-Landau, 2000).

Growth and development determine the time at which the propagules mature. Thus, the timing of the abscission of propagule in the first instance controlled by phenology, which is in turn influenced by degree-day sums and day length (Cleland et al., 2007). Growth and development are themselves modified by the availability of resources such as soil moisture and nutrients. Taghizadeh et al., (2012) demonstrated, for instance, that water deficit promotes seed maturation and thus timing of seed dispersal in *Raphanus raphanistrum* L. (wild radish). Application of fertilizer in agroecosystems can have an influence on the timing of seed dispersal in weeds. In this sense, Scursoni and Arnold (2002) demonstrated a relationship between seed dispersal and timing of nitrogen application. They found that late application of nitrogen fertilizer reduce pre-harvest seed dispersal of *Avena fatua* (wild oat) in *Hordeum vulgare* (barley). Soil fertility is also likely to have a major influence over water and nutrients. However, there is also an interaction between resource availability and growth and development of the mother plant: the more the plant grows, the more these resources become depleted. If plants are growing in dense populations or low nutrient condition, these resources will become depleted more rapidly (i.e. competition), thus affecting further growth and ultimately seed maturation and timing of dispersal.

Climate, soil and crop species determine the timing of cultivation and sowing and hence the timing of crop and weed growth. Crop species will determine the intensity of competition, while many environmental factors and field history influence weed density. The type of the crop in which weeds are growing affects morphological and phenological characteristics of the weeds and hence their seed dispersal. Once again, these will impact on dispersal via their influence on plant growth and development. Clearly, if we are to fully understand dispersal phenomenon, we need to investigate the ways that these “components” of seed dispersal interact. The literature does not provide the effect of crop and nutrients, specifically nitrogen, on the nitrogen content of weeds and consequently timing of seed dispersal, though see Scursoni and Arnold (2002). This information could help ecological management of agricultural weeds through management of seed dispersal.

The objective of this study was to explore further factors which cause variation in timing of seed maturation and dispersal. We used two agricultural weeds, wild barley (*Hordeum spontaneum* Koch.) and wild mustard (*Brassica kaber* (DC.)), as case study growing within wheat (*Triticum aestivum* L. cv. Shiroodi) and oilseed rape (*Brassica napus*) cropping systems, as neighbouring plants. It was sought to determine: (1) the influence of nitrogen levels on timing of seed maturation and dispersal, and (2) the effect of the crop species in which the weed is growing on timing of seed maturation and seed dispersal. It was hypothesised that increasing nitrogen level would lengthen growth and development resulting in a delay in seed maturation and the onset of seed dispersal and then lengthening the duration of seed “rain”, and that a closely related crop would conversely advance seed maturation and the onset of seed dispersal resulting in shortening of seed "rain" duration in its weedy relative.

Results

Maturation and timing of seed dispersal

The results of this study showed that nitrogen significantly ($P \leq 0.05$) affect maturation and consequently timing of seed dispersal in *H. spontaneum* and *B. kaber* in both cropping systems (Tables 1 and 2). *Hordeum spontaneum* seeds developed under no or low nitrogen levels (0 and 60 kg ha^{-1}) reached their final maturation stage sooner than those developed under the high nitrogen levels (120 and 240 kg ha^{-1}). With increasing nitrogen from 0 to 240 kg ha^{-1} seed maturation of *H. spontaneum* in wheat and oilseed rape delayed 138 and 83 degree-days respectively (Table 1). This resulted in a delay of 109 and 76 degree-days for seed dispersal of *H. spontaneum* in both cropping systems correspondingly. In all nitrogen levels, the time of seed maturation and subsequently seed dispersal of *H. spontaneum* took place sooner where growing in wheat than in oilseed rape cropping system (Table 1). With increasing nitrogen from 0 to 240 kg ha^{-1} the proportion of *H. spontaneum* seeds dispersed decreased by about 15 and 13 % in wheat and oilseed rape cropping systems respectively though it was not significant where the weed grew in oilseed rape cropping system (Table 1).

Nitrogen application elicited a delay in pod maturation of *B. kaber* in both cropping systems; however it was not significant when grown in oilseed rape (Table 2). With increasing nitrogen from 0 to 240 kg ha^{-1}, pod maturation delayed about 127 and 150 degree-days in wheat and oilseed rape cropping systems respectively (Table 2). In all nitrogen levels, *B. kaber* pods matured sooner when plants grown in oilseed rape cropping system than in wheat. In contrast to *H. spontaneum*, *B. kaber* pods remained on the plant during the experiment and they required a physical force to dehisce. However, a very few pods dehisced perhaps due to gravity. With increasing nitrogen from 0 to 240 kg ha^{-1}, the final pod length of *B. kaber* increased in both wheat and oilseed rape cropping systems by 69% and 57% respectively (Table 2).

Nitrogen content of weeds and crop tissues

To fully understand mechanism of nitrogen on seed dispersal, nitrogen content of *H. spontaneum* (both in seeds and in straw) were measured. The results showed that nitrogen content of *H. spontaneum* increased significantly ($P \leq 0.05$) in both cropping systems by increasing nitrogen (Table 3). The effect of nitrogen fertilizer on nitrogen content of *H. spontaneum* straw was higher than on the seed nitrogen content in both cropping systems. However, *H. spontaneum* showed higher nitrogen content in its seeds than in the straw. The results also showed that *H. spontaneum* has higher nitrogen content of seeds and straw when grown in wheat cropping systems than in oilseed rape (Table 3). With increasing nitrogen from 0 to 240 kg ha^{-1}, nitrogen uptake by seeds and straw of *H. spontaneum* increased significantly ($P \leq 0.05$) in both wheat and oilseed rape cropping systems, however there was no significant difference between two cropping systems (Table 4). Nitrogen content in *B. kaber* seeds was higher than its straw in both cropping systems and with increasing nitrogen from 0 to 240 kg ha^{-1} nitrogen content of seed and straw increased by about 31 % and 9% respectively where the weed grown in wheat. In contrast, these were 7% and 29% respectively when it was grown in oilseed rape cropping system (Table 5). Furthermore, nitrogen content of straw in *B. kaber* plants grown in wheat was significantly ($P \leq 0.01$) higher than where the plants grown in the oilseed rape cropping system (Table 5). With increasing nitrogen from 0 to 240 kg ha^{-1}, nitrogen uptake per plant in *B. kaber* seeds and straw increased significantly ($P \leq 0.05$) by about 175 % and 125% respectively where the weed grown in wheat, whereas it increased significantly ($P \leq 0.05$) about 550% and 300% where the weed grown in oilseed rape

Table 1. The influence of nitrogen level on maturation and timing of seed dispersal of *H. spontaneum* grown in two cropping systems.

Cropping system	Nitrogen	Maturation time[a]	Dispersal time	Seeds dispersal
	kg ha^{-1}	GDD	GDD	%
Wheat	0	1079 c	1180 b	35.6 a
	60	1171 b	1264 a	29.4 ab
	120	1175 b	1272 a	24.6 ab
	240	1217 a	1290 a	20 b
	LSD (0.05)	39	75	15
Oilseed rape				
	0	1194 a	1262 b	29.7 a
	60	1216 a	1282 b	26 a
	120	1221 a	1302 ab	22.5 a
	240	1277 a	1338 a	17 a
	LSD(0.05)	130	46	18
P[b]		**P≤ 0.05**	**≤ 0.05**	**≤ 0.05**

[a]Values followed by different letters are significantly ($P \leq 0.05$) different. [b] Paired samples *t*-test comparing wheat and oilseed rape cropping systems. Significant results are shown in bold.

Table 2. The influence of nitrogen level on maturation and final pod length of *B. kaber* grown in two cropping systems.

Cropping system	Nitrogen	Maturation time[a]	Dispersal time	Pod length
	kg ha^{-1}	GDD		cm
Wheat	0	1315 b	-	2.4 b
	60	1393 a	-	2.7 b
	120	1414 a	-	3.8 a
	240	1442 a	-	4.1 a
	LSD (0.05)	67	-	0.34
Oilseed rape				
	0	1257 a	-	2.4 c
	120	1405 a	-	3.7 ab
	240	1408 a	-	3.7 a
	LSD (0.05)	77	-	0.34
P [b]		**≤ 0.05**		> 0.05

[a]Values followed by different letters are significantly ($P \leq 0.05$) different. [b] Paired samples *t*-test comparing wheat and oilseed rape cropping systems. Significant results are shown in bold.

Table 3. Nitrogen concentration in seeds and straw of *H. spontaneum* grown in wheat and oilseed rape cropping systems.

		Nitrogen in[a]:	
Cropping System	Nitrogen	Seeds	Straw
Wheat	kg ha^{-1}	%	
	0	2.59 c	0.62 c
	60	3.11 b	0.85 b
	120	3.32 b	1.19 a
	240	3.62 a	1.19 a
	LSD (0.05)	0.27	0.13
Oilseed rape			
	0	2.11 c	0.44 b
	60	2.76 b	0.44 b
	120	3.00 ab	0.72 a
	240	3.10 a	0.76 a
	LSD (0.05)	0.31	0.20
P[b]		**≤ 0.01**	**≤ 0.01**

[a]Values followed by different letters are significantly ($P \leq 0.05$) different. [b] Paired samples *t*-test comparing wheat and oilseed rape cropping systems. Significant results are shown in bold.

Table 4. Nitrogen uptake by seeds and straw of *H. spontaneum* grown in wheat and oilseed rape cropping systems.

Cropping System	Nitrogen	Nitrogen uptake[a]: Seeds	Straw	Total
	kg ha^{-1}	mg/plant		
Wheat	0	25.98 c	6.98 c	32.96 c
	60	46.88 b	15.65 bc	62.52 b
	120	52.15 b	19.99 b	72.13 b
	240	77.90 a	30.08 a	107.98 a
	LSD(0.05)	19.36	9.97	28.43
Oilseed rape				
	0	17.92 b	2.92 c	20.84 c
	60	34.12 b	6.77 bc	40.89 c
	120	65.57 a	19.34 b	84.91 b
	240	82.92 a	46.14 a	129.06 a
	LSD (0.05)	20.15	15.96	20.43
P[b]		> 0.05	> 0.05	> 0.05

[a]Values followed by different letters are significantly ($P \leq 0.05$) different. [b]Paired samples *t*-test comparing wheat and oilseed rape cropping systems.

Table 5. Nitrogen concentration in seeds and straw of *B. kaber* grown in wheat and oilseed rape cropping systems.

Cropping System	Nitrogen	Nitrogen in[a]: Seeds	Straw
	kg ha^{-1}	%	
Wheat	0	4.4 b	0.85 a
	60	5.4 a	0.86 a
	120	5.7 a	0.89 a
	240	5.8 a	0.93 a
	LSD (0.05)	0.5	0.22
Oilseed rape			
	0	5.4 a	0.64 c
	60	5.4 a	0.69 bc
	120	5.6 a	0.74 b
	240	5.8 a	0.83 a
	LSD (0.05)	0.7	0.08
P[b]		> 0.05	**≤ 0.01**

[a]Values followed by different letters are significantly ($P \leq 0.05$) different. [b] Paired samples *t*-test comparing wheat and oilseed rape cropping systems. Significant results are shown in bold.

Table 6. Nitrogen uptake by seeds and straw of *B. kaber* grown in wheat and oilseed rape cropping systems.

Cropping System	Nitrogen	Nitrogen uptake[a]: Seeds	Straw	Total
	kg ha^{-1}	mg/plant		
Wheat	0	174.31 c	147.75 b	322.07 d
	60	412.96 b	170.77 b	583.73 c
	120	475.04 b	243.41 ab	718.45 b
	240	580.82 a	332.07 a	912.89 a
	LSD(0.05)	95.88	160.97	118.35
Oilseed rape				
	0	60.99 b	21.06 c	82.05 b
	60	94.68 b	44.89 b	139.47 b
	120	350.67 a	75.60 a	426.28 a
	240	390.12 a	86.04 a	476.16 a
	LSD(0.05)	116.96	15.67	118.09
P[b]		**≤ 0.05**	**≤ 0.01**	**≤ 0.01**

[a]Values followed by different letters are significantly ($P \leq 0.05$) different. [b] Paired samples *t*-test comparing wheat and oilseed rape cropping systems. Significant results are shown in bold.

cropping system (Table 6). Finally, the total nitrogen uptake per plant increased about 180 % and 480 % where *B. kaber* grown in wheat and oilseed rape cropping systems respectively (Table 6). In overall, *B. kaber* was less able to uptake nitrogen where grown in oilseed rape compared in wheat cropping system (Table 6).

Discussion

The first aim of this study was to understand the effects of nitrogen on seed maturation and timing of seed dispersal. Clearly the results have shown that seed maturation and timing of seed dispersal in both *H. spontaneum* and *B. kaber* are influenced by the amount of nitrogen fertilizer used in the wheat and oilseed rape cropping systems. The second aim was to determine the extent to which the neighbouring plants, crop species, affect seed maturation and timing of seed dispersal. The results presented showed that maternal environment and neighbouring crops, markedly affected maturation time and hence the timing of dispersal in *H. spontaneum* and *B. kaber* in wheat and oilseed rape cropping systems. These results will be discussed in detail.

The availability of resources is an important factor affecting the maturation and the timing of seed release. This study showed that the lack of nitrogen during the plant growth, mainly reproductive stage, is an important regulating factor for the timing of seed maturation and seed dispersal in *H. spontaneum* and *B. kaber*. As a consequence there was a positive relationship between nitrogen availability and the timing of seed maturation and seed dispersal (Tables 1 and 2). There are numerous cases recorded of seed traits, in particular dormancy and germination, being modified by resources availability and environmental factors operating during seed development and maturation (Baskin and Baskin, 2014; Fenner and Thompson, 2005; Lehnhoff et al., 2013). It has been investigated that lack of water, as one of the most important resources, affects seed attribute including dispersal. For example, Taghizadeh et al., (2009) demonstrated that water deficit increased the size of the cells in the abscission zone of wild radish (*Raphanus raphanistrum* L.), and abscission scar diameter increased by ~50% with increasing water deficit. This promoted the onset of pod dehiscence.

To better understand the effect of phenology on seed dispersal, Taghizadeh et al., (2012) also showed that for cohorts of fruits initiated at the same time, those that developed under mild and severe water deficit reached their final length sooner, and were dispersed sooner, than those receiving an abundant supply of water. Furthermore, where seeds have developed and matured while the parent plant was under resource deficit (e.g. water deficit at flowering, late emergence and competition with crop), these seeds have reduced longevity (Young, 2001). Such results raise questions about the effects of availability of other resources (e.g. nitrogen) on the timing of seed dispersal. We hypothesized that the increase of nitrogen level will lengthen growth and development resulting delay in seed maturation and the onset of seed dispersal. The results of this study indicate that two species grown under different levels of nitrogen supported this hypothesis. In both cropping systems where plants developed under abundant nitrogen condition, their maturation and dispersal considerably delayed than those plants developed under low or zero nitrogen levels. This is because photosynthetic rate, chlorophyll and nitrogen contents, and leaf area index increase simultaneously by nitrogen. In fact, plants grown with low levels of nitrogen senesce soon while plants grown with high levels of nitrogen continue to accumulate assimilates (Gyuga et al., 2002).

It is well appreciated that in many temperate and Mediterranean species, reproductive development is initiated by day length or low temperature, though once reproduction has been triggered the rate of growth of floral structures is then positively correlated with temperature. Our results showed that nitrogen availability could also well influence on the onset of seed dispersal in annual weed *H. spontaneum* grown in wheat.

The data presented in this study showed a negative relationship between nitrogen rate and the percentage of seeds dispersed from the parent plant. By increasing nitrogen rate the percentage of *H. spontaneum* seeds dispersal reduced significantly when grown in wheat and oilseed rape. Dispersal is an important process for generation succession of a species to unoccupied habitats. The process is also a defence mechanism against environmental stresses such as water changes (Taghizadeh et al., 2009).

We also hypothesized that a closely neighbouring crop would conversely advance seed maturation and the onset of seed dispersal resulting in shortening of seed "rain" duration in its weedy relative. Our experimental maturation and dispersal data in *H. spontaneum* support this hypothesis and clearly show a bias towards faster maturation and consequently seed dispersal at the closely related crop, wheat. Although *B. kaber* species studied in this experiment did not show abscission and dispersal during this study, pod maturation for plants grown in oilseed rape was significantly ($P \leq 0.05$) sooner than that for plants grown in wheat (GDD 1358 vs 1391). Lehnhoff et al., (2013) demonstrated that relative canopy height of the barley crop influences wild oat (*Avena fatua*) seed viability, dormancy, and germination and ecologists increasingly recognize that the height of neighbouring plants influence the distance travelled by seeds resulting in different plant/ weed pattern distribution in the ecosystems/agroecosystems (for example see Cousens et al., 2008a; Davies and Sheley, 2007). However, timing of seed dispersal among plant neighbours that share same space and resources, e.g. weed species in their closely related field crops, has been less documented. This study provides an experimental evidence that timing of seed dispersal in *H. spontaneum* plants is neighbouring crop species dependent and not entirely a property of individual weed or disperser agents.

It is well appreciated that many weeds are high consumers of nitrogen (Carlson and Hill, 1986; Qasem, 1992; Teyker et al., 1991). Our results show that not only nitrogen availability increases growth and development of associated weeds more than the crop, it also postpones their timing of seed dispersal. Where management practices aim to catch weed seeds at crop harvest, nitrogen availability then would prevents weeds to disperse their seeds before crop harvest and reduce the ability of the weed to increase its population in the next generation in the field.

The results of this study have important implications for managing agricultural weeds via managing seed dispersal. The success of weed management based on ecological principles and weed biology will depend on a better understanding of the effects of environment on life history strategies, growth and the ability to predict phenology of seed dispersal. By understanding variables that drive phenology of seed dispersal, new approaches and more long-term solutions for weed problems can be developed. The data presented in this study showed that the timing of seed maturation and seed dispersal is influenced by resource (nitrogen) availability and neighbouring crop species. In terms of management, reducing total input of weed seeds to the soil seed bank is a rational long term weed management (Cousens and Mortimer, 1995; Goplen et al., 2016; Hill et al., 2016; Schwartz et al., 2016). This can be achieved by curtailing seed production and/or harvesting seeds before and/or after they are dispersed to the ground (Walsh and Parker, 2002; Walsh et al., 2013). Our results showed that this strategy could be improved further by management of nitrogen fertilizer and selecting crop species which end their life cycle at the desired phenological stage of the weed in order to reduce quantity of weed seed input to the soil seed bank.

Materials and Methods

Plant materials and experimental designs

To study the effects of environmental conditions, namely nitrogen and neighbouring crop species on timing of seed maturation and seed dispersal of agricultural weeds, two experiments were undertaken at Darab Faculty of Agriculture and Natural Resources (54°3/E, 28°59/N), Shiraz University, Iran, in growing season 2010-2011. The experimental site has a silty loam soil, pH=7.8 with average annual rainfall of 270 mm. A monocot weed, *H. spontaneum*, and a dicot weed, *Brassica kaber*, were grown in wheat and oilseed rape cropping systems.

The first experiment was set-up on a wheat field. *Hordeum spontaneum* and *B. kaber* seeds were harvested in June 2009 from populations located in several wheat fields of Darab town. The experimental design was a randomized complete block design, with a 4 × 2 factorial arrangement of treatments and three replicates. Treatments included four nitrogen (N) levels (0, 60, 120 and 240 kg ha^{-1}) and two type of weeds (*H. spontaneum* and *B. kaber*). Individual plots were 2 × 2.2 m with 0.5 m between them and 1 m between blocks. Eleven rows of winter wheat were sown by hand at 140 kg ha^{-1} in rows spaced 20 cm and the sowing depth of 3 cm on 6 January 2010. To measure the precise effects of the neighbouring crops on the weeds, nine plants of *H. spontaneum* or *B. kaber* were established in each plot. Clumps of four weed seeds were sown at a depth of 2 cm in alternate spaces between crop rows in a diamond grid pattern. After emergence, seedlings were thinned to two and finally one per clump when it was considered that the last one would survive to maturity. The distance between weed plants within a row space was 60 cm. The weed seeds were planted at the same time as the crop. Nitrogen fertilizer was added to the experimental plots in three crop growth stages: planting, tillering and stem elongation (Zadoks et al., 1974), and in each step as 1/3 to plots.

The second experiment was also arranged as a randomized complete block design with a 4 × 2 factorial with four nitrogen levels (0, 60, 120 and 240 kg N ha^{-1}) and the same type of weeds as in experiment 1 (*H. spontaneum* and *B. kaber*) grown in oilseed rape crop. Individual plots were 2 × 2 m with 0.5 m between them and 1 m between blocks. Five rows of oilseed rape (cv. RGS003) were planted at 8 kg ha^{-1} in rows spaced 40 cm. Weed plants (*H. spontaneum* or *B. kaber*) were again established in each plot as in experiment 1. Nitrogen fertilizer was added to the experimental plots in three oilseed rape crop growth stages: planting, stem elongation and before flowering, and in each step as 1/3 to the experimental plots.

Data extraction

In both experiments, two types of data were collected: (1) Growth and development of individual weed plants and their seed dispersal (2) Nitrogen content of tissue for both weeds and the crop.

In both cropping systems, three plants of *H. spontaneum* and *B. kaber* were randomly selected from the middle of each plot and were tagged using a colour waterproof ribbon to determine the timing of seed maturation and then the date at which seeds depart the parent plant (timing of seed dispersal). Three seeds/fruit were tagged randomly on each selected plant. These seeds/fruits were monitored daily at the end of growing season when their colour changed from green to brown or yellow. The day at which the seeds/fruit were missing was then considered as dispersal date. To analyse these data they were converted to Growing Degree Days (GDD). Growing Degree Days were calculated from the average of daily maximum and minimum air temperatures. A base temperature of 6 °C and 4 °C were considered for *H. spontaneum* and *B. kaber* respectively. Both crops were harvested on 29 May 2011.

In both cropping systems three crop and weed plants were harvested from each plot randomly at the maturation stage and their N content were measured. N concentration of seeds and straws for each species were separately determined by Kjeldahl method (Kjeldahl, 1883). Total N uptake (mg $plant^{-1}$) was then calculated as total biomass produced by a species (seed plus straw) with total N concentration using:

(seed dry weight × seed nitrogen concentration + straw dry weight × straw nitrogen concentration)×10

Statistical analyses

All statistical analyses were performed using the General Linear Model or Mixed procedures within SAS and means compared using least significant difference (LSD) tests at $P \leq 0.05$. As the data sets were unbalanced the normality was tested using Minitab statistical software (Release 14). Paired samples t-test (SPSS, V. 20) was used to test the statistical significance of the effect of cropping systems on the measured parameters.

Conclusion

The present study provides evidence that nitrogen and the type of the neighbouring crop affect timing of seed maturity and consequently seed dispersal in two agricultural weeds; *Hordeum spontaneum* Koch. and *Brassica kaber* (DC.). There was a positive relationship between nitrogen availability and the timing of seed maturation and seed dispersal. *H. spontaneum* seeds developed under no or low nitrogen levels reached their final maturation stage sooner than those developed under high nitrogen levels. This resulted in an earlier seed dispersal. We also experimentally demonstrated that timing of seed dispersal in *H. spontaneum* plants is neighbouring crop species-dependent. *H. spontaneum* seeds that developed in wheat crop reached their maturation stage sooner, and were then dispersed sooner than those developed in oilseed rape. These results add a new and important information on timing of weed seed dispersal within cropping systems and provide an opportunity for crop growers to reduce weed seed return to their fields by managing seed dispersal.

Acknowledgment

This research was financially supported by Shiraz University, Iran.

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