PLANT&FOREST

Assessing persistence of cruciferous crops in the field

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Abstract

We assessed the persistence of eight major cruciferous crops—leaf mustard, oilseed rape, cabbage, broccoli, cauliflower, Chinese cabbage, turnip, and radish—growing in the field. In the first part of our experiment, we tested the viability of seeds that had been buried at two different soil depths for up to 16 months. We then broadcast seeds over the soil surface and left them undisturbed to investigate the survivorship of the resultant plants over two years. Seed viability was significantly affected by plant taxa and burial depth, but not substantially affected by the duration of burial. Although seeds of leaf mustard had the greatest viability among all crops examined here, the viability rates were significantly lower at 2 cm depth than at 15 cm. Seeds of leaf mustard, oilseed rape, broccoli, turnip, and Chinese cabbage remained viable throughout the 16-month period. A study of plant demography revealed that only leaf mustard and oilseed rape succeeded in producing seeds and overwintering in the undisturbed field. However, neither of those species competed well with other plants long-term and their overall growth and survival rates declined during the evaluation period. In addition, insect herbivory severely decreased the growth of all of these crops. Our results suggest that populations of leaf mustard and oilseed rape do not tend to persist in the field for more than a few years without disturbance and external seed inputs.

Keywords: Brassica juncea, Brassica napus, cruciferous crops, persistence

Introduction

Cruciferous crops, originating in the Mediterranean regions, Europe, and Asia, are an important mainstay of the world’s food supply (Dixon, 2007). With the advent of bioengineering technologies, those crops have been successfully transformed, and transgenic oilseed rape is now commercially cultivated in the US, Canada, and Australia. Although such cultivation is not yet allowed in South Korea, transgenic cruciferous crops have been developed and are being field-tested there (Kim et al., 2015; 2018).
Cultivation of transgenic crops on a commercial scale raised concerns about the potential effects of transgenic crops on human health and environment (Lee et al., 2021). One major concern associated with the release of transgenic plants into the environment is the possibility that they will persist there in the absence of human intervention. In particular, species that can maintain self-sustaining populations could disrupt natural biotic communities in the ecosystem and also reduce crop productivity (Parker and Kareiva, 1996; Wolfenbarger and Phifer, 2000; Snow et al., 2005).

Studies of oilseed rape persistence have shown that plants can survive in arable fields for as long as 8 to 15 years (Pessel et al., 2001; D’Hertefeldt et al., 2008; Belter, 2016). Since imported seeds of transgenic herbicide-resistant oilseed rape spilled in Japan in 2005, plants have been found around nearby grain-receiving ports (Saji et al., 2005; Mizuguti et al., 2011; Nishizawa et al., 2016). Although most of those transgenic populations have not survived long-term, others have thrived (Mizuguti et al., 2011). Additional discoveries of transgenic herbicide-resistant oilseed rape plants along transportation routes have been reported in South Korea (Shin et al., 2016; Lee, 2020; Yi and Lee, 2021), Germany (Franzaring et al., 2016), Switzerland (Schoenenberger and D’Andrea, 2012; Hecht et al., 2014), Australia (Busi and Powles, 2016), Canada (Yoshimura et al., 2006), and the US (Schafer et al., 2011). In 2017, transgenic oilseed rape seed that had not been authorized for planting unintentionally contaminated an overseas shipment of conventional seed that was imported into South Korea, and seedlings were later found in many parks or agricultural fields at 56 locations in that country (MAFRA, 2017). These incidents are evidence that the ecosystems of importing countries, where transgenic crops are not being cultivated, can be unintentionally exposed to them when seed lots become contaminated or when seed is spilled during transportation. Although oilseed rape is known to persist in agricultural and natural environments, little information is available about other cruciferous species that might eventually be commercialized as transgenic crops.

Here, we assessed eight major crucifers—leaf mustard, oilseed rape, cabbage, broccoli, cauliflower, Chinese cabbage, turnip, and radish. To assess their persistence in the field, we first calculated the viability rates for seeds buried in soil for up to 16 months. In a second set of experiments, we broadcast seeds on the soil surface, left them undisturbed, and then investigated the survivorship of plants over two years.

**Materials and methods**

**Plant materials**

Seeds of the following were purchased commercially in March 2014: leaf mustard (*Brassica juncea* [L.] Czern.), oilseed rape (*B. napus* L.), cauliflower (*B. oleracea* var. *botrytis* L.), cabbage (*B. oleracea* var. *capitata* L.), broccoli (*B. oleracea* var. *italica* Plenck), and turnip (*B. rapa* var. *rapa* L.), all from Asia Seed Co., Ltd.; Chinese cabbage (*B. rapa* var. *glabra* Regel), from Syngenta Korea Ltd.; and radish (*Raphanus sativus* L.), from Hungnong Seed Co., Ltd.

**Study site**

Field experiments were conducted at the Korea Research Institute of Bioscience & Biotechnology (KRIBB), Cheongju, Republic of Korea (36°43'04"N, 127°26'07"E, elevation: 37 m). The soil was neutral with a sandy loam texture. Between March 2014 and May 2016, we obtained data for daily air temperature and rainfall using an automatic weather station (ENCOSYS, Anyang, Korea). During the entire study period, the mean monthly air temperature ranged from -2.3 to 25.8°C and the total precipitation was 1,718.8 mm (Fig. 1).
Seed burial experiment

On 21 March 2014, we established four blocks in a research field that had been plowed during November 2013. Each block contained eighty 25 cm × 25 cm plots. We filled individual nylon mesh bags (5 cm × 10 cm; mesh width, 0.2 mm) with 25 cm³ of autoclaved sand and added 50 seeds of a single crop variety. In total, 10 bags per plant taxa were buried in the center of each block, at either 2 cm or 15 cm deep, according to a randomized complete block design (8 taxa × 2 depths × 5 sampling times × 4 replicates = 320 plots total). During the study period, the plots remained undisturbed.

To test the initial viability of seeds, we placed 100 seeds per taxa (× four replications) on moist filter paper (Advantec, Tokyo, Japan) in Petri plates (90 mm diam). The seeds were incubated in a growth chamber (20°C, 16 h photoperiod). Germinated seeds were counted and removed from the plates at 2 d intervals. After the first 10 d of incubation, seed coats of non-germinated seeds were scarified with sand paper and incubated for another 10 d, again with the number of germinants being recorded every second day. Soft, easily squashed seeds were classified as dead and those not easily crushed were considered hard seeds. Overall viability was calculated as the percentage of germinated seeds plus hard seeds out of 100 total seeds.

Seed bags were retrieved from the field at 1, 2, 4, 8, and 16 months after burial, and the contents were spread over a 1-mm soil sieve (Chung Gye Industrial Mfg. Co., Seoul, Korea) to separate the components. The seeds were washed with distilled water and then sterilized for 10 min with 10% sodium hypochlorite (Sigma-Aldrich, St. Louis, MO, USA). We applied the method described above to determine their viability.

Plant demography

On 24 March 2014, four blocks (eight 1 m × 1 m plots each) were established in a field that had been plowed in November 2013. We followed a randomized complete block design (8 taxa × 4 replicates = 32 plots total). Each plot was separated by a 1 m wide alley that was mulched with non-woven polypropylene fabric mat to prohibit plant growth. After seeds from each taxa were broadcast in each plot, the field was left undisturbed and was not watered.
Beginning at Week 2 after sowing, we counted the number of emerging seedlings at two-week intervals. Each new individual of a taxon was initially marked with a toothpick. Seedlings that had grown into mature plants were marked with yellow tape to identify those within the same cohort. On each census date, survival and shoot growth were measured for single crop plants.

We also determined the number of plants at each growth stage (i.e., seedling, rosette, bolting, flowering, and ripening). For leaf mustard and oilseed rape, which produced seeds during the study, we randomly selected four plants per taxa and counted the total number of pods. From those selections, we randomly sampled 10 pods per plant (40 pods total) and tallied the number of seeds per pod.

The dynamics of the entire plant community within each plot was investigated at two-week intervals, beginning at seven weeks after our seeds were broadcast. Every two weeks, we recorded the percentage of plant cover for all species found there, along with maximum heights and survival rates. All plants were identified using ‘Coloured Flora of Korea’ (Lee, 2003) and ‘New Illustrations and Photographs of Naturalized Plants of Korea’ (Park, 2009). Nomenclature followed that of the Korean Plant Names Index (KNA, 2016).

**Statistical analysis**

We investigated the effects of plant taxa, burial depth, and burial duration on seed viability, using a three-way analysis of variances. Because seeds of cabbage, cauliflower, and radish buried at either 2 or 15 cm were not viable at any sampling point, we did not include their data in our statistical analysis.

**Results**

**Viability of seeds buried in soil**

The initial seed viability for our eight cruciferous crops ranged from 85.3 to 99.5% (Table 1). After the burial experiment began, we found no viable seeds of cabbage, cauliflower, or radish at either soil depth because they had either already germinated or deteriorated within the first month of the test. Results from the analysis of variance for leaf mustard, oilseed rape, Chinese cabbage, broccoli, and turnip showed that overall viability at 16 months post-burial was significantly affected by taxa (F = 129.9, p < 0.001). The rate was significantly higher for leaf mustard than for any other species. Seed viability was also significantly greater for Chinese cabbage than for oilseed rape, broccoli, or turnip.

Burial depth also had an important impact (F = 354.3, p < 0.001), with viability being significantly lower at 2 cm than at 15 cm. Throughout the entire observation period, we found no viable seeds of oilseed rape, broccoli, turnip, and Chinese cabbage at 2 cm. Furthermore, although seeds of leaf mustard were viable at this shallower depth, the rate was only 16% of the level recorded at 15 cm.

Duration of burial had no significant influence on seed viability (F = 0.224, p = 0.925). Although those rates were reduced within one month of burial when compared with the initial level, we detected no decreasing trend in viability as the burial time was prolonged. Moreover, seeds of leaf mustard, oilseed rape, broccoli, turnip, and Chinese cabbage remained viable throughout the 16 month period.
Assessing persistence of cruciferous crops in the field

We identified three cohorts for leaf mustard and oilseed rape (Figs. 2 and 3). In 2014, Cohort 1 of leaf mustard emerged in April, produced fruit, and then died in August 2014 (Figs. 2A and 3A). For Cohort 2, the seedlings emerged in September 2014 and overwintered as rosettes (Figs. 2A and 3B). In 2015, those plants from Cohort 2 produced fruit from May to July and died in August. Cohort 3 seedlings emerged from July to November in 2015, overwintered as rosettes, produced fruit in May, and survived through the end of the study period in June 2016 (Figs. 2A, 3C, and 4G). For oilseed rape, Cohort 1 emerged in April 2014, produced fruit from June to July, and survived up to August 2015 (Figs. 2B and 3A). The Cohort 2 seedlings emerged in September 2014, overwintered as rosettes, produced fruit from May to August, and died in August 2015 (Figs. 2B, 3B, and 4H). Seedlings in Cohort 3 emerged in July but died in August 2015 (Figs. 2C and 3C).

Whereas Cohort 1 seedlings of cauliflower, broccoli, Chinese cabbage, turnip, and radish emerged in April 2014 (Fig. 2C), no cabbage seedlings were produced during the study period (Fig. 3A). Cauliflower, turnip, and radish plants did not bolt at any time, but died in August 2014 (Figs. 2C and 3A). Although the broccoli plants did bolt, they failed to flower and those Cohort 1 plants died during Winter 2014 (Figs. 2C, 3A, and 4F). Likewise, Chinese cabbage bolted but did not flower before dying in August 2014 (Figs. 2C and 3A).

The leaves on most of our cruciferous crops—especially the cauliflower, broccoli, Chinese cabbage, turnip, and radish—were severely damaged by insect herbivores, including *Athalia rosae* (Hymenoptera: Tenthredinidae), *Pieris rapae* (Lepidoptera: Pieridae), and *Plutella xylostella* (Lepidoptera: Plutellidae) (Figs. 4B - E).

For leaf mustard, seed numbers per pod were lower in Cohort 2 than in Cohort 3 (Table 2). However, the number of pods per plant for that taxon did not differ among cohorts (Table 2). For oilseed rape, both seed number per pod and pod number per plant were greater for Cohort 2 than for Cohort 1 (Table 2).

### Table 1. Percentage of cruciferous crop seeds viable for 1 to 16 months at two soil depths (2 cm and 15 cm).

<table>
<thead>
<tr>
<th>Plant taxa</th>
<th>Initial viability (%)</th>
<th>Burial depth (cm)</th>
<th>Months after burial</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Brassica juncea</em></td>
<td>97.8 ± 0.9</td>
<td>2</td>
<td>4.5 ± 1.5</td>
<td>3.5 ± 2.4</td>
<td>3.5 ± 1.0</td>
<td>7.0 ± 2.9</td>
<td>7.5 ± 2.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>41.0 ± 4.9</td>
<td>46.5 ± 7.5</td>
<td>44.5 ± 1.9</td>
<td>46.0 ± 2.9</td>
<td>47.5 ± 3.3</td>
<td></td>
</tr>
<tr>
<td><em>B. napus</em></td>
<td>91.0 ± 1.9</td>
<td>2</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>15</td>
<td>6.0 ± 0.8</td>
<td>3.0 ± 1.3</td>
<td>2.0 ± 0.8</td>
<td>3.0 ± 1.0</td>
<td>3.0 ± 1.3</td>
<td></td>
</tr>
<tr>
<td><em>B. oleracea var. botrytis</em></td>
<td>98.3 ± 0.5</td>
<td>2</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td></td>
</tr>
<tr>
<td><em>B. oleracea var. capitata</em></td>
<td>98.8 ± 0.5</td>
<td>2</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td></td>
</tr>
<tr>
<td><em>B. oleracea var. italica</em></td>
<td>99.5 ± 0.3</td>
<td>2</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
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<tr>
<td></td>
<td></td>
<td>15</td>
<td>7.5 ± 1.3</td>
<td>7.0 ± 1.0</td>
<td>7.5 ± 2.2</td>
<td>9.0 ± 3.0</td>
<td>3.5 ± 2.4</td>
<td></td>
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<tr>
<td><em>B. rapa var. rapa</em></td>
<td>85.3 ± 1.0</td>
<td>2</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
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<tr>
<td></td>
<td></td>
<td>15</td>
<td>7.0 ± 2.1</td>
<td>5.0 ± 1.7</td>
<td>1.5 ± 1.0</td>
<td>1.0 ± 0.6</td>
<td>2.5 ± 1.9</td>
<td></td>
</tr>
<tr>
<td><em>B. rapa var. glabra</em></td>
<td>99.5 ± 0.5</td>
<td>2</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>24.0 ± 11.6</td>
<td>17.0 ± 5.2</td>
<td>21.0 ± 4.9</td>
<td>20.5 ± 5.2</td>
<td>17.5 ± 1.5</td>
<td></td>
</tr>
<tr>
<td><em>Raphanus sativus</em></td>
<td>98.0 ± 0.7</td>
<td>2</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
<td></td>
</tr>
</tbody>
</table>

Data are means ± standard errors (n = 4).

**Persistence of cruciferous crops after broadcasting seeds on soil**

We identified three cohorts for leaf mustard and oilseed rape (Figs. 2 and 3). In 2014, Cohort 1 of leaf mustard emerged in April, produced fruit, and then died in August 2014 (Figs. 2A and 3A). For Cohort 2, the seedlings emerged in September 2014 and overwintered as rosettes (Figs. 2A and 3B). In 2015, those plants from Cohort 2 produced fruit from May to July and died in August. Cohort 3 seedlings emerged from July to November in 2015, overwintered as rosettes, produced fruit in May, and survived through the end of the study period in June 2016 (Figs. 2A, 3C, and 4G). For oilseed rape, Cohort 1 emerged in April 2014, produced fruit from June to July, and survived up to August 2015 (Figs. 2B and 3A). The Cohort 2 seedlings emerged in September 2014, overwintered as rosettes, produced fruit from May to August, and died in August 2015 (Figs. 2B, 3B, and 4H). Seedlings in Cohort 3 emerged in July but died in August 2015 (Figs. 2C and 3C).

Whereas Cohort 1 seedlings of cauliflower, broccoli, Chinese cabbage, turnip, and radish emerged in April 2014 (Fig. 2C), no cabbage seedlings were produced during the study period (Fig. 3A). Cauliflower, turnip, and radish plants did not bolt at any time, but died in August 2014 (Figs. 2C and 3A). Although the broccoli plants did bolt, they failed to flower and those Cohort 1 plants died during Winter 2014 (Figs. 2C, 3A, and 4F). Likewise, Chinese cabbage bolted but did not flower before dying in August 2014 (Figs. 2C and 3A).

The leaves on most of our cruciferous crops—especially the cauliflower, broccoli, Chinese cabbage, turnip, and radish—were severely damaged by insect herbivores, including *Athalia rosae* (Hymenoptera: Tenthredinidae), *Pieris rapae* (Lepidoptera: Pieridae), and *Plutella xylostella* (Lepidoptera: Plutellidae) (Figs. 4B - E).

For leaf mustard, seed numbers per pod were lower in Cohort 2 than in Cohort 3 (Table 2). However, the number of pods per plant for that taxon did not differ among cohorts (Table 2). For oilseed rape, both seed number per pod and pod number per plant were greater for Cohort 2 than for Cohort 1 (Table 2).
Fig. 2. Mean number of surviving plants in cohorts examined from 2014 to 2016. Seeds of cruciferous crops were broadcast on soil in March 2014. (A) *Brassica juncea*, (B) *B. napus*, (C) *B. oleracea* var. *botrytis*, *B. oleracea* var. *italica*, *B. rapa* var. *rapa*, *B. rapa* var. *glabra*, and *Raphanus sativus*. 
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Fig. 3. Mean number (± standard error) of cruciferous plants at different growth stages. Seeds were broadcast on soil in March 2014. Cohorts 2 and 3 were found only for Brassica juncea and B. napus. Bj, B. juncea; Bn, B. napus; Boc, B. oleracea var. capitata; Bob, B. oleracea var. botrytis; Boi, B. oleracea var. italica; Br, B. rapa var. rapa; Brg, B. rapa var. glabra; Rs, Raphanus sativus.

Fig. 4. Representative photographs of (A) test plots dominated by Chenopodium album (8 July 2014), (B) Brassica oleracea var. botrytis (26 May 2014), (C) B. rapa var. glabra (26 May 2014), (D) Raphanus sativus (26 May 2014), (E) B. rapa var. rapa (27 May 2014), (F) B. oleracea var. italica (23 December 2014), (G) B. juncea (16 March 2016), and (H) B. napus (8 July 2015).
Plant coverages and heights

We present plant community data only for plots of leaf mustard and oilseed rape because they were the only two crops to maintain their populations for more than one year. In both 2014 and 2015, the coverage (%) of *Chenopodium album* (Fig. 4A) was the greatest among whole plots (Figs. 5A and 5B). For 2014, the level of coverage was 46.8% for leaf mustard and 47.5% for oilseed rape, with those percentages being initially greater than for any other plants in those communities. However, after the leaf mustard and oilseed rape achieved their maximum heights (121.5 cm and 94.5 cm, respectively; Figs. 5C and 5D) in early June 2014, plants of *C. album* were much taller (maximum height: 274.5 cm). In 2015, plants of *Erigeron annuus* and *E. canadensis* increased in number per plot, but their relative coverages were much lower than those for leaf mustard (maximum cover: 13.5%; maximum height: 41.8 cm), oilseed rape (maximum cover: 12.5%; maximum height: 66.8 cm), or the *C. album* plants. From March to May 2016, the abundance of *Cerastium glomeratum* was the greatest in the leaf mustard plots, where the maximum coverage and height recorded for that crop was 6.3% and 43.5 cm, respectively. Cohort 3 of oilseed rape did not survive to grow in 2016.

Table 2. Reproductive traits of *Brassica juncea* and *B. napus* plants from seeds broadcast in March 2014.

<table>
<thead>
<tr>
<th>Trait</th>
<th>Cohort 1</th>
<th>Cohort 2</th>
<th>Cohort 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Brassica juncea</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seed (number·pod⁻¹)</td>
<td>16.1 ± 0.6</td>
<td>15.1 ± 0.6</td>
<td>18.2 ± 0.8</td>
</tr>
<tr>
<td>Pod (number·plant⁻¹)</td>
<td>231.0 ± 61.8</td>
<td>382.3 ± 112.9</td>
<td>478.8 ± 256.5</td>
</tr>
<tr>
<td><em>B. napus</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seed (number·pod⁻¹)</td>
<td>10.5 ± 0.9</td>
<td>13.8 ± 1.2</td>
<td>-</td>
</tr>
<tr>
<td>Pod (number·plant⁻¹)</td>
<td>107.0 ± 41.9</td>
<td>799.5 ± 375.7</td>
<td>-</td>
</tr>
</tbody>
</table>

Data are means ± standard errors (n = 4). Cohort 3 of *B. napus* failed to produce seeds.

Fig. 5. Changes in mean coverage (%; n = 4) and heights (cm, n = 4) of *Brassica juncea* and *B. napus*, and representative plants occurring in plots broadcast with seeds of (A, C) *B. juncea*, and (B, D) *B. napus* in March 2014.
Discussion

Seeds of cauliflower, cabbage, and radish lost viability within the first month after their burial regardless of soil depth. Although seeds of oilseed rape, broccoli, turnip, and Chinese cabbage placed at 2 cm deep also lost viability within one month, they remained viable for up to 16 months when buried at 15 cm. Furthermore, viability of leaf mustard seed at 16 months after burial was greater at 15 cm than at 2 cm. This ability to maintain viability in deeper soil might have been due to a lack of light, smaller fluctuations in soil temperature and moisture content, or reduced gas exchange (Sparrow et al., 1990; Pekrun et al., 1998; Benvenuti et al., 2001). Therefore, it is advisable that one avoid post-harvest tillage in agricultural fields where volunteer oilseed rape becomes weedy because that practice can incorporate those seeds into soil where their dormancy is induced and a seed bank is built up (López-Granados and Lutman, 1998).

Even if hard seeds were to germinate after a long dormant period, it is unlikely that plants of broccoli, turnip, or Chinese cabbage would persist in a non-agricultural field based on our observations that they competed poorly during our trials. In fact, when seeds of cabbage, broccoli, cauliflower, Chinese cabbage, turnip, and radish were broadcast on the soil surface and then germinated, their seedlings failed to grow, produce flowers and seeds, or survive through winter. Therefore, they were unable to maintain their initial population levels.

In contrast to those of other taxa tested here, the seeds of leaf mustard and oilseed rape remained viable throughout the study period, with rates at 15 cm deep being 48% for the former and 3.0% for the latter after 16 months. This result is similar to findings reported by Crawley et al. (1993), who showed that seed survival during the first year of burial was less than 2% for non-transgenic as well as transgenic oilseed rape. We also calculated rates of 3.5% and 2.5% for broccoli and turnip.

Among our selection of cruciferous crops, only leaf mustard and oilseed rape succeeded in producing seeds and overwintering in the field. Whereas the former continued from Cohort 1 through Cohort 3, the latter produced seed only within Cohorts 1 and 2, and seedlings of Cohort 3 did not survive. For both of those taxa, the number of seedlings in each cohort declined as the generations increased. Changes in coverage and heights showed that plants of leaf mustard and oilseed rape survived the winter and produced seeds before other plants in the plots had emerged. However, that advantage was lost when strong competitors, including C. album or E. canadensis, became more aggressive in their growth rates. Overall, neither leaf mustard nor oilseed rape competed well in the long term, and both their performance and survivability were diminished over time. In addition, insect herbivory severely reduced the growth of all tested cruciferous crops. They included Pieris rapae, Plutella xylostella, and Athalia rosae, all of which are major pests in the cultivation of such crops (Lamb, 1989; Nagasaka and Ohsaki, 2002; Hooks and Johnson, 2003). We have previously reported that these are particularly abundant in fields where cabbage plants are raised (Kim et al., 2015).

Our results are consistent with those described by Meffin et al. (2015), who indicated that most feral Brassica populations (e.g., turnip, oilseed rape, leaf mustard, and cabbage) in Canterbury, New Zealand, are transient and unlikely to persist without external seed inputs. Although feral transgenic oilseed rape has been growing along transportation routes in Japan since 2005, populations around ports tend to be maintained only because of new spills and are not otherwise persistent (Katsuta et al., 2015). Busi and Powles (2016) have also found that populations of transgenic oilseed rape in natural bushland areas are maintained for no more than four years. Likewise, Crawley and Brown (1995, 2004) have shown that, due to rapid secondary succession, feral oilseed rape population will become locally extinct within one to four years if new seed is not repeatedly introduced into the area. Oilseed rape is considered as an early successional ruderal.
Investigating wild leaf mustard growing along the riversides of Japan, Yoshimura et al. (2016) have demonstrated that the average number of seeds per pod is 8.36 (95% confidence interval: 7.69 - 9.04) while the number of pods per plant is 470 (95% confidence interval: 310 - 710). When compared with the data tallied in this current study, the presence of more seeds per leaf mustard plant found here was probably a result of us obtaining seeds from a commercial source.

In summary, among the eight cruciferous crops examined here, only seeds from leaf mustard and oilseed remained viable in the soil for up to 16 months, and those taxa were the only two that continued to produce new generations of seedlings. However, both were highly susceptible to insect herbivory and neither competed well with other plants in our sampling plots. Therefore, we conclude that these two taxa would not likely persist in a field for more than a few years without additional disturbances or external seed inputs.

Conflict of Interests

No potential conflict of interest relevant to this article was reported.

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