Chapter 5 Better Control of Imported Cabbageworm, *Pieris rapae*, in Organic Brassicas in the Eastern United States

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NON-TECHNICAL SUMMARY

The cabbage butterfly (*Pieris rapae*, Lepidoptera: Pieridae) is the common white butterfly that we see in our gardens. The immature stage, referred to as the imported cabbageworm, feeds on broccoli, kale, and a variety of other vegetable plants in the genus *Brassica* (Brassicaceae). These larvae damage plants by chewing on the leaves, and severe infestations can cause complete defoliation. While *P. rapae* is one of the most common butterflies in the United States, it is a non-native invasive pest that reached North America in the 1860s. At that time, a very limited effort was made to use its European natural enemies against it. This effort resulted in the establishment of one parasitoid, *Cotesia glomerata* (Hymenoptera: Braconidae). This parasitoid, while becoming common, did little to reduce the damage caused by imported cabbageworm. A century later (from the 1960s through 1988), an attempt was made to introduce a different species, *Cotesia rubecula*, whose biology was more likely to provide some control of this pest. In 1988, introduction of *C. rubecula* from China succeeded. Work in New England showed that this new parasitoid reduced the damage done by *P. rapae* caterpillars in non-sprayed organic vegetable farms by 75%. The introduction of *C. rubecula* also reduced *C. glomerata* by more than 90%, which allowed a native, non-pest white butterfly, *Pieris oleracea*, to start expanding its range after a century of decline.

HISTORY OF INVASION AND NATURE OF PROBLEM

Pieris rapae (**Fig. 1**) (Lepidoptera: Pieridae) is a common pest of brassica crops (Brassicaceae or the mustard family) in Eurasia that was first found in North America in Quebec, Canada in 1860, possibly transported on stored cabbages on ships. By 1869, it was recorded in Boston, Massachusetts (Scudder, 1889). It soon became a common and important pest in the United States on cabbage and, over time, in all related brassica crops in both gardens and commercial fields (Chittenden, 1926). Biological control efforts in the 1880s

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Figure 1. The imported cabbageworm, *Pieris rapae.* (Ansel Oommen, Bugwood.org CC BY-NC 3.0 US)

Figure 2. The native veined white, *Pieris oleracea.* (Susan Elliott, iNaturalist.org CC BY-NC 4.0)

(Clausen, 1978) eventually led to displacement of a native butterfly, the veined white (*Pieris oleracea*) (**Fig. 2**), from southern New England due to the introduction of the parasitoid *Cotesia glomerata* (Hymenoptera: Braconidae) (Benson et al., 2003a). New biocontrol efforts were not made until the 1960s through the 1980s. In 1988, the successful establishment of a more specialized parasitoid (*Cotestia rubecula*) (Van Driesche and Nunn, 2002) provided better control of the pest and, by outcompeting *C. glomerata*, allowed the veined white to begin to re-establish and spread in southern New England (Herlihy et al., 2014).

WHY CONTROL THIS INVASIVE SPECIES?

High levels of feeding by *P. rapae* caterpillars reduce yield and quality of brassica plants (cabbage, broccoli, Brussels sprouts, kale, collards) in both commercial fields and gardens. Without controls of some type, losses can be significant (e.g., Bare, 1940; Wolfenbarger and Hibbs, 1958). In commercial conventional fields, a variety of syntethic pesticides are widely and commonly used. On organic vegetable farms, pesticides, including products containing the bacterium *Bacillus thuringiensis,* and others approved approved by organic producers' organizations are used in a similar way.

THE ECOLOGY OF THE PROBLEM

Pieris rapae is an important pest of brassica crops, but it co-occurs with other leaf-feeding pests such as diamondback moth (*Plutella xylostella*) and cabbage looper (*Trichoplusia ni*), which also must be controlled for good crop production (Anon., 2002). *Pieris rapae* also feeds on many species of native and invasive mustards, which can sustain *P. rapae* populations outside of crop fields (Wagner, 2005). Adult butterflies produced in these non-crop areas can rapidly disperse over large areas and infest crops. Consequently, control in production fields is not aimed at long-term or regional control but rather at protecting the immediate crop, usually through conventional or organic pesticides or possibly using protective row covers over plants in the field during the most vulnerable periods of each crop (Adams et al., 1990). Cabbage and broccoli become relatively less susceptible to this pest as they mature. In contrast, Brussels sprouts, collards, and kale are attacked throughout the growing season.

Classical biological control can contribute to the reduction of this *P. rapae* damage in two ways. First, specialized parasitoids can reduce the numbers of the pest produced on non-crop mustard weeds in non-cultivated areas. This lowers the regional pool of invading adults available to attack newly planted crop fields. Secondly, on organic farms, parasitism by *C. rubecula* parasitoids can avoid up to 70% of the crop damage by killing larvae while they are still small (4th instar) (Rahman, 1970) rather than allowing them to become mature (5th instar).

PROJECT HISTORY THROUGH AGENT ESTABLISHMENT

Three parasitoids were released in North America against *P. rapae*; *Cotesia glomerata* and *Cotesia rubecula* are both braconids that attack young larvae while *Trichogramma evanescens* (Hymenoptera: Trichogrammatidae) is an egg parasitoid (Clausen, 1978; Van Driesche and Nunn, 2002). A fourth resident species, *Pteromalus puparum* (Hymenoptera: Pteromalidae), attacks the chrysalis (pupal stage) of *P. rapae*; *P. puparum* either was accidentally introduced into North America (Clausen, 1978) or is native (having been recorded in Canada in 1844 [Scudder, 1889]). *Pteromalus puparum* also attacks pupae of butterflies in several other families (Barron et al., 2003). Although *P. puparum* sometimes causes high rates of parasitism in *P. rapae* pupae collected from non-sprayed brassica crops (Lasota and Kok, 1986), by itself it does not reduce damage from *P. rapae*.

Use of the egg parasitoid *T. evanescens* was based on its seasonal mass release, rather than the action of established populations. Following mass releases, *T. evanescens* was recovered for a short time in release fields (Oatman et al., 1968). When used as a biological pesticide (whereby releases are made of thousands of wasps reared in commercial insectaries), it has shown promise for control at the field level (Parker, 1970; Oatman and Platner, 1972). However, it does not appear to either establish or spread. Therefore, it is likely not present in fields where it has not been released (e.g., Shelton et al., 2002) or in wild weedy mustard plants. Augmentative releases of insectary-reared *T. evanescens* are not presently used against *P. rapae* in the United States, likely due to the cost of such releases (relative to the cost of pesticides), limited availability of *T. evanescens* from suppliers, and the difficulty of integrating such releases with pesticides used for control of other pests in conventional brassica crops.

Cotesia glomerata (**Fig. 3**), a larval parasitoid of *P. rapae* in Europe, was chosen for importation by the USDA in the 1880s based on brief surveys in England and Germany. After some initial failures (Clausen, 1978), the parasitoid's cocoons were imported from England, and the adults that emerged were released in 1884, resulting in the establishment of *C. glomerata* in eastern North America (Clausen, 1978). In Europe, *C. glomerata* is principally a parasitoid of the large white (*Pieris brassicae*); however, in North America *C. glomerata* adapted well to the small white (= imported cabbageworm), *P. rapae*. Because *C. glomerata* produces many offspring (20–100) in each caterpillar it attacks, this parasitoid spread widely and became common. Two disadvantages of *C. glomerata* were that it has a wide host range (discussed in a later section) and that it does not kill imported cabbageworms until they are fully grown. It was subsequently shown that parasitized caterpillars eat more than healthy caterpillars (Clausen, 1978). Consequently, even high rates of *C. glomerata* parasitism do not reduce damage in individual fields.

Figure 3. The parasitoid *Cotesia glomerata.* (David Marquina Reyes, iNaturalist.org CC BY-NC_ND 4.0)

Figure 4. The parasitoid *Cotesia rubecula.* (David Cappaert, Bugwood.org CC BY-NC 3.0 US)

In contrast to *Cotesia glomerata*, *C. rubecula* (**Fig. 4**) produces only one offspring in each caterpillar that it attacks. However, *C. rubecula* kills caterpillars while they are still small, therefore avoiding more than 70% of the feeding damage that would otherwise occur (Rahman, 1970). Efforts to establish *C. rubecula* in the United States were not initially successful, most likely due to a poor match between the climate where the wasps were collected (in the former Yugoslavia) and where they were released in the central and eastern United States (Nealis, 1985). However, a population of this parasitoid was discovered in British Columbia in the 1960s, presumably from an unknown introduction. This strain was redistributed to Missouri, New Jersey, South Carolina, and Ontario (Puttler et al., 1970), but generally failed to establish, except perhaps in Ontario (Corrigan, 1982). A second attempt to establish the species in the eastern United States was made by collecting it in the former Yugoslavia, which was believed to be a better climate match than the previous attempt because its cold winters were more like the intended release areas. Wasps from Yugoslavia were released in Missouri, Virginia, and Ontario, and in 1988 it was recovered in Virginia, but that population did not persist. A third attempt was then made using wasps obtained from Beijing, China whose climate was a good match to New England. Wasps collected from China were released from 1988 to 1993 at 17 locations in Massachusetts, Connecticut, and Rhode Island, and the species established easily and spread rapidly (Van Driesche and Nunn, 2002). Further releases were subsequently made in additional states.

HOW WELL DID IT WORK

What Impacts Really Matter?

What matters to farmers faced with infestations of imported cabbageworms is the level of damage in their crops. If that can be measured, it is the best assessment of how well any control measures have worked. However, this is complicated because populations of imported cabbageworm exist both inside crop fields and in the much greater expanse of uncultivated meadows and river borders where sunny fields support native and introduced species of wild mustard plants suitable as food for *P. rapae* caterpillars.

Single samples of the pest and its parasitoids taken from a farmer's field can only partially show how important a biocontrol agent might be (a method commonly called "sample percent parasitism"). A better approach is to calculate how each life stage of the pest survives or dies over a whole generation of the pest, and what kills the individuals that die. This approach is called building life tables, which are similar to the actuarial tables used by life insurance companies to set insurance rates for human policy holders. Life tables sum up events over a whole generation of the pest and show which types of mortality are most important. An important feature that affects what farmers care most about—how much damage happens—is exactly how old caterpillars are when they die. There are five life stages of caterpillars (called instars) for imported cabbageworm, and nearly 70% of the total feeding by a caterpillar is due to feeding in the final 5th instar, which can be a thousand times more than a newly hatched caterpillar (Rayman, 1970). Control measures that kill larvae before they reach that stage are much more effective at reducing damage. In the following section we consider the effects of *C. rubecula* on *P. rapae* in view of these various ways to measure parasitoid impact on a pest.

Impact in Research Plots and Farm Surveys

In the mid-1980s in Massachusetts, before the introduction of *C. rubecula* from China, I measured rates of parasitism of *P. rapae* larvae due to *C. glomerata* and found them to be in the 60–80% range in a patch of non-sprayed collard plants (a brassica crop that remains suitable for *P. rapae* egg laying all season) (Van Driesche, 1988). Using information from this study, I constructed life tables that confirmed *C. glomerata* really was an important mortality factor affecting the changes in *P. rapae* numbers from one pest generation to the next in my collard field (Van Driesche and Bellows, 1988). However, due to the biology of *C. glomerata*, all the mortality caused by *C. glomerata* occurred in fully grown 5th-instar caterpillars. So, pest damage in the crop was not reduced.

In 2007, nine years after I had released *C. rubecula* from a Chinese population, that parasitoid was well established in southern New England. To find out how common and widespread it was, I surveyed organic vegetable farms in central and western Massachusetts in spring, toward the end of the first generation of *P. rapae* in various brassica crops. I found *C. rubecula* parasitizing young *P. rapae* caterpillars at every one of the 20 locations I sampled (based on 30 or more caterpillars from each site). In those samples, *C. rubecula* had attacked 75% of the caterpillars collected. Only 1% of these caterpillars had been attacked by *C. glomerata* (Van Driesche, 2008). In 2009, I repeated this survey in the same general area at 21 farms, but I sampled in the fall during the last generation of *P. rapae* to see how the levels of *C. rubecula* attack might compare to the spring in 2007 (**Fig. 5**). I found the same overall rate of parasitism, 75%, and a modestly higher proportion of that was from *C. glomerata* (12% of all parasitized hosts) (Herlihy and Van Driesche, 2013).

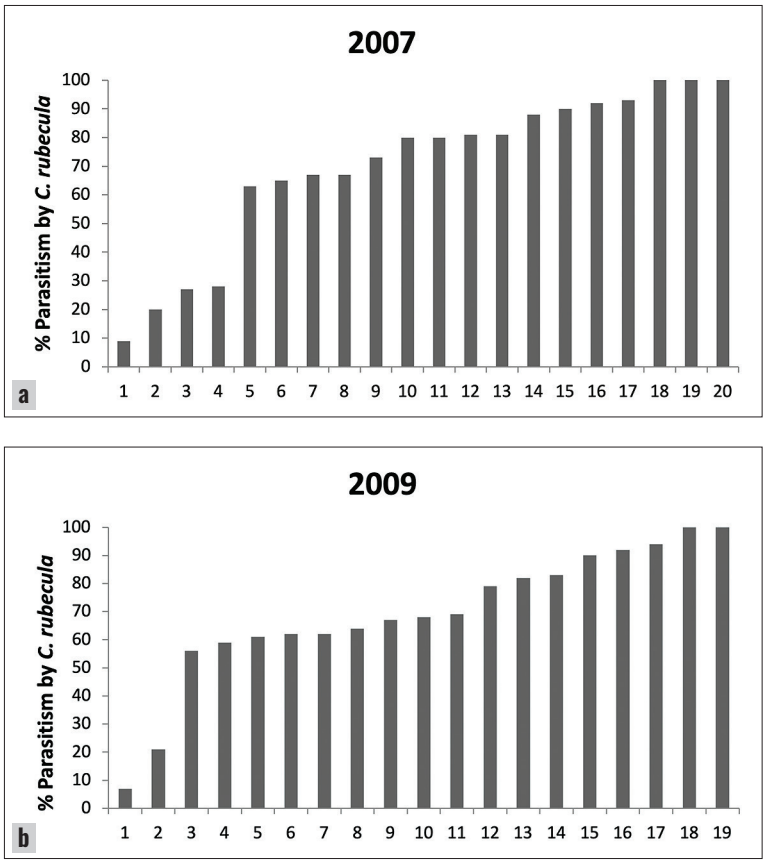

Figure 5. Rates of parasitism by *Cotesia rubecula* in western Massachusetts organic vegetable farms in (a) spring of 2007 and (b) fall of 2009, both surveys showing an average rate of parasitism of 75%. (modified from Herlihy and Van Driesche, 2013)

In a detailed field experiment at one organic collard farm in western Massachusetts in 2011, we measured the survival of imported cabbageworm caterpillar groups initiated on four different start dates throughout the growing season. Parasitism by *C. rubecula* averaged 62.4% among the measured caterpillar groups. No parasitism by *C. glomerata* was observed. Most importantly, parasitism by *C. rubecula* reduced crop damage because parasitized *P. rapae* larvae died when they were still small (4th instars) and did not become the large 5th-instar caterpillars that do most of the damage (Herlihy and Van Driesche, 2013).

The above findings in Massachusetts are supported by similar findings in New Zealand where *P. rapae* also invaded and where *C. rubecula* was also intentionally introduced. In the New Zealand study, *C. rubecula*

caused 70% parasitism; cumulatively this level of parasitism lowered the density of the largest caterpillars (5th instars) at harvest by 85% (from 1.65 to 0.25 caterpillars/plant), greatly reducing plant damage (Cameron and Walker, 2002).

Regional Impact of *Cotesia rubecula*

To see how far the Chinese strain of *C. rubecula* had spread and whether the high level of parasitism we saw in Massachusetts was widespread, a survey was conducted in September of 2011 in 14 states and two Canadian provinces, from New England to North Dakota, southward to North Carolina and northward to New Brunswick and Quebec. We found *C. rubecula* all the way west to North Dakota (our furthest observation point). It had become the dominant parasitoid of imported cabbageworm in the northeastern and north central United States and adjacent parts of southeastern Canada and had displaced the previously common *C. glomerata* in that area. However, we found that *C. glomerata* remained dominant in more southern areas, from Virginia to North Carolina and westward to southern Illinois (below latitude N 38° 48') (Herlihy et al., 2012).

Side Effects of this Biocontrol Project

In addition to the main effect of controlling the pest *P. rapae*, there were three side effects caused by this biocontrol project: one negative (in the 1880s) and two positive (in the 1980s). The harmful effect was the attack on non-target native butterflies by *C. glomerata*, and the two positive effects were the subsequent suppression of *C. glomerata* by the second parasitoid, *C. rubecula*, and then the recovery of *P. oleracea*, the native butterfly that had nearly disappeared from Massachusetts due to *C. glomerata*. We investigated all three of these side events in Massachusetts, and the details are given in the following sections.

Harm to native butterflies by *Cotesia glomerata*

Cotesia glomerata attacks butterflies in three genera, including several species of *Pieris* in Europe and North America (Puttler et al., 1970; Lees and Archer, 1974; Laing and Levin, 1982; Sato and Ohsaki, 1987), several *Tatochila* in Chile (where *C. glomerata* was also introduced) (A. Sharpiro, pers. comm.), and one *Aporia* in Asia (Jiang, 2001). In laboratory tests in New England, we found that both of our native white butterflies—*P. oleracea* (the veined white) and *Pieris virginiensis* (the West Virginia white)—were suitable hosts for *C. glomerata* (Van Driesche et al., 2003). However, in the field we only found attacks on *P. oleracea* (Benson et al., 2003a) because *C. glomerata* did not fly in the forested areas where *P. virginensis* is found. Placement of *P. rapae* caterpillars in forests did not attract any attacks by *C. glomerata*, indicating *P. virginensis* is not at risk (Benson et al., 2003b).

Reduction of *Cotesia glomerata* by *C. rubecula*

Collections of *P. rapae* caterpillars at organic vegetable farms in western Massachusetts showed that within 20 years of its introduction, *C. rubecula* had replaced *C. glomerata* as the dominant parasitoid of *P. rapae* at sites that were widely separated in forested, hilly country (Van Driesche, 2008; Herlihy and Van Driesche, 2013). By 2007–2009, *C. glomerata* had been reduced to only 1% of total parasitism in the spring survey (2007) and 12% in the fall survey (2009). Similar results were reported from a study in New Zealand where in plots without *C. rubecula*, the parasitism by *C. glomerata* was 10–60%, but in plots with *C. rubecula* present, it was less than 10% (Cameron and Walker, 2002).

It is likely that the displacement of *C. glomerata* by *C. rubecula* in Massachusetts happened much sooner than the dates of our 2007–2009 surveys. In the research plot of collards where we made

Figure 6. The invasive form of cuckoo flower, *Cardamine pratensis* var. *pratensis* (a) has been a key reason for the population rebound of the veined white butterfly, *Pieris oleracea*, in Massachusetts, because its (b) ground-hugging rosette provides a suitable host from April to November. (a: Tomás Curtis; b: Graham Buck; a,b: iNaturalist.org CC BY-NC 4.0)

our first releases of *C. rubecula* in 1988, we observed that densities of *C. glomerata* cocoon masses had declined by 81% between 1988 and 1990, just two years after release of *C. rubecula*. We measured this decline as the percentage of the sampled plants on which we found *C. glomerata* cocoon piles. Specifically, in 1988 the number of sampled plants bearing *C. glomerata* cocoons was 16% (661 plants with cocoons/4,098 plants sampled over the growing season), but this had dropped to just 3% (82 plants with *C. glomerata* cocoons/2,706 plants sampled) by 1990, just two years after release of *C. rubecula* at this site (Van Driesche and Nunn, 2002).

Recovery of the native butterfly *Pieris oleracea*

Pieris oleracea (formerly *P. napi oleracea*) was historically the common white meadow butterfly of southern New England. In the mid-to-late nineteenth century, its range in Massachusetts declined (Scudder, 1889) to just remnant populations in western Massachusetts, and then was presumed to have disappeared. However, in 1986, a single large population of *P. oleracea* was discovered in western Massachusetts in a wet meadow where the caterpillars fed on an introduced variant of a wild mustard called cuckoo flower. This plant, *Cardamine pratensis* var. *pratensis* (**Fig. 6a**), is a spring-blooming biennial that is present throughout the year as a ground-hugging rosette (**Fig. 6b**).

We undertook studies to understand why this site supported a large population of the butterfly and to understand its likely future status. We observed that at this site, cuckoo flower's rosettes remained suitable for the butterfly's caterpillars from May through November, allowing for the development of four *P. oleracea*e generations each year (Herlihy et al., 2014). For most of the growing season, cuckoo flower's rosettes were over-topped by other species of plants, leading us to question if this provided any protection to caterpillars from parasitism. To find out, we introduced *C. glomerata* adults into open-bottomed field cages placed over either tall vegetation or similar areas where the tall vegetation had been removed by clipping. We placed *P. oleracea* caterpillars in these cages by putting them on either small collard or cuckoo flower plants in pots and placing the pots on the ground. In cages with

over-topping vegetation, caterpillars suffered significantly lower *C. glomerata* parasitism (22.2%, 18/81 recovered larvae) compared to cages from which the tall plants had been removed by clipping (72.9%, 62/85 recovered larvae) (Herlihy et al., 2014). This suggested that even in the presence of *C. glomerata* populations in the habitat, this new host plant provided significant protection against parasitism because it was hidden most of the year by larger plants.

The second factor we found to have affected the native butterfly's improved survival was the displacement of *C. glomerata* (which attacks *P. oleracea*) by *C. rubecula* (which does not). Historically, the decline of *P. oleracea* began after the invasion of *P. rapae* (Scudder 1889), but there was no evidence of any strong competition between the butterflies' caterpillars for food. Research in Massachusetts showed that *C. glomerata*, which was the dominant parasitoid of *P. rapae* during this period of *P. oleracea* decline (Van Driesche and Bellows, 1988), could parasitize *P. oleracea* (Van Driesche et al., 2003) and did so in field tests (Benson et al., 2003a).

Chronologically, events were as follows. In 1986, a single large surviving population of *P. oleracea*e was discovered on cuckoo flower in western Massachusetts. We believe *C. glomerata* had long been long present at that site because in 2001 we found that 100% of trap host larvae of *P. oleracea*e were parasitized by *C. glomerata* (Van Driesche et al., 2004) in a cow pasture just 52 km (30 miles) away from the surviving population of *P. oleracea*. In 2007, we showed that *C. glomerata* was present at the cuckoo flower/*P. oleracea* site (Van Driesche, 2008), but at a much lower level that in our 2001 study (Van Driesche et al., 2004). From 2008 to 2010, we exposed *P. oleracea* larvae on potted plants with over-topping vegetation at the site with the *P. oleracea* population to try to detect parasitism. Of the 417 *P. oleracea* larvae recovered after field exposure in those experiments, only 3 (0.7 %) were parasitized by *C. glomerata* (and none by *C. rubecula*) (Herlihy et al., 2014). These studies demonstrated that by 2007 (the date we showed *C. glomerata* had been displaced by *C. rubecula* [Van Driesche, 2008]), pressure of *C. glomerata* on the native *P. oleracea* was gone at this site (Herlihy et al., 2014).

In summary, when *P. oleracea* adopted the invasive plant cuckoo flower as a new host, this conferred some degree of protection from *C. glomerata* because the plant's rosettes were obscured most of the year by taller vegetation that interfered with parasitoid foraging. Also, cuckoo flower provided an abundant resource that was available for the whole growing season, allowing four generations of the butterfly per year. These host plant benefits, combined with the removal of threats from *C. glomerata* (due to its displacement by *C. rubecula*), enhanced the population growth rate and hence density of the native butterfly. We expect that the butterfly's population will now re-expand across its historical range in Massachusetts.

BENEFITS OF BIOLOGICAL CONTROL OF IMPORTED CABBAGEWORM

There were two clear benefits from the introduction of *C. rubecula* for biological control of imported cabbageworm. The first of these was a 75% reduction in the number of large caterpillars in organic brassica crops, with a corresponding reduction in damage. This benefit is potentially offset to some degree because other pests also attack brassica crops, and their control is still necessary. However, it does provide benefits where pesticides are not applied, as in organic farms and many home gardens. The other benefit has been the suppression of another parasitoid, *C. glomerata*, which has largely eliminated the harm it caused to a native butterfly, the veined white (*P. oleracea*).

WORK STILL TO BE DONE

This story has been developing for over three decades, and while the broad outlines are now clear, there are several points that remain to be investigated. These include the degree of impact of *C. rubecula* and *C. glomerata* on *P. rapae* in non-cultivated habitats (meadows and along the margins of larger rivers) where

imported cabbageworm feeds on invasive species of mustards. The rate of parasitism by these two *Cotesia* species on *P. rapae* outside of farm fields is worth exploring because this habitat is quite extensive, and these patches of wild mustards are potentially a large source of the butterfly and its associated parasitoids. Secondly, I predict that the range of the veined white, *P. oleracea*, will increase over time and will follow increases in the range of the introduced cuckoo flower. The veined white is also likely to increasingly be able to feed on weedy mustards in meadows and along rivers as the pressure of *C. glomerata* declines. Surveys of the veined white in southern New England are needed to track the recovery of this butterfly over more of its historical range.

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