

CHAPTER
10

Biological Control of Cereal Leaf Beetle in the United States

Charles H. Pickett

California Department of Food and Agriculture, Sacramento, CA charlie.pickett@cdfa.ca.gov

NON-TECHNICAL SUMMARY

Cereal leaf beetle, *Oulema melanopus* (Coleoptera: Chrysomelidae), is one of the most serious pests of small grain crops worldwide. Without specialized natural enemies, this beetle can significantly reduce yields of wheat and oats, which are food crops important to large parts of the world. Native to Eurasia, cereal leaf beetle invaded North America in the early 1960s when it was first recorded in the United States in Michigan. The beetle quickly began to spread through wheat-growing regions and was soon the target of a regional eradication program by the USDA-APHIS. Within a few years, it was obvious that pesticides weren't going to slow the spread of cereal leaf beetle, and pesticides were a major cost to producers of various grain crops. In 1964, efforts were initiated to develop grain varieties resistant to feeding by this pest and to find parasitoids associated with cereal leaf beetle in its native range. The USDA-ARS European Parasite Laboratory, now called the European Biological Control Laboratory, spent six years (1964–1969) searching for parasitoids closely associated with cereal leaf beetle throughout Europe. Four species with promise for use in biological control were shipped to the United States, and eventually two of these became permanently established in the eastern United States. The larval parasitoid *Tetrastichus julis* (Hymenoptera: Eulophidae) was the most successful and quickly established new populations. *Anaphes flavipes* (Hymenoptera: Mymaridae), which attacks the egg stage of the beetle, also established permanent populations in the eastern United States in the 1960s and 1970s. By 1999, the cereal leaf beetle had spread across Canada and the Pacific Northwest grain-growing regions. Initially, growers in midwestern, eastern, and northwestern U.S. states applied pesticides to control the pest, but without achieving sustainable control. Following some success of the biological control program against cereal leaf beetle in the eastern United States, the two most successful parasitoids were obtained and shipped to Washington, Oregon, and nearby states. Recoveries of *A. flavipes* were never recorded in this region or Utah. However, parasitism of larvae by *T. julis* reached high levels in field insectaries designed to aid establishment of these parasitoids. Farmer pesticide-use records, required in Oregon, showed that as the larval parasitoid spread, the amount of pesticide used for cereal leaf beetle control in Oregon declined (Roberts and Rao, 2012).

The beetle was first reported in northern California in 2013. Within one year of that observation, *T. julis* was collected in central Oregon for release just across the border in northern California. A field insectary was established at the University of California (UC) Research and Extension Center in Tulelake, California to produce *T. julis* for release throughout the Klamath River Basin grain production area of northern California. Between the natural dispersal of parasitoids from this insectary, redistribution of the parasitoid, and its natural spread from Oregon south into California, high levels of parasitism were soon recorded from nearby commercial small grain fields. Within five years (2018), numbers of cereal leaf beetle in grain fields declined significantly. Control of this pest with pesticides in northern California and the Pacific Northwest cost several million dollars per year, and these savings, following the success of this biological control program, were directly passed on to regional grain growers. Furthermore, the non-target effects of routine insecticide treatments to such common crops as wheat and oats was avoided.

HISTORY OF INVASION AND NATURE OF PROBLEM

The Species Invasion

Cereal leaf beetle (CLB), *Oulema melanopus* (Coleoptera: Chrysomelidae), is a serious pest of small grains and grass forage (**Fig. 1**). Native to Eurasia, the beetle was first reported in the United States in Michigan in 1959 (Dysart et al., 1973), and was formally identified as a new pest in North America in 1962. The beetle rapidly spread eastward but was slower in its westward movement (Haynes and Gage, 1981). By mid 1980s, CLB could be found in Montana, Idaho, and Utah, and it was first reported in Washington State in 1999 (Rao et al., 2003; Evans et al., 2006; Roberts, 2016). Populations can now be found throughout much of the continental United States except for the drier, warmer regions of the Southwest (southern California, Arizona, New Mexico, Texas, Oklahoma) where it has yet to be reported. The beetle has also spread north and can be found throughout the cereal-growing regions of Canada (Kher et al., 2013). Cereal leaf beetle was first reported in northern California along the Oregon border in 2013 (Dowell and Pickett, 2016).

The CLB was first found in the grain belt of the United States, and because it is such a serious pest of wheat and oats, the first response to CLB by the USDA was to limit its spread and achieve eradication (Haynes and Gage, 1981). In 1962, townships in Michigan and Indiana were placed in quarantine, and all small grains had to be treated before leaving these areas. Millions of bushels of hay, straw, and small grains were treated with insecticides. Repeated spraying of several hundred thousand acres of these same commodities

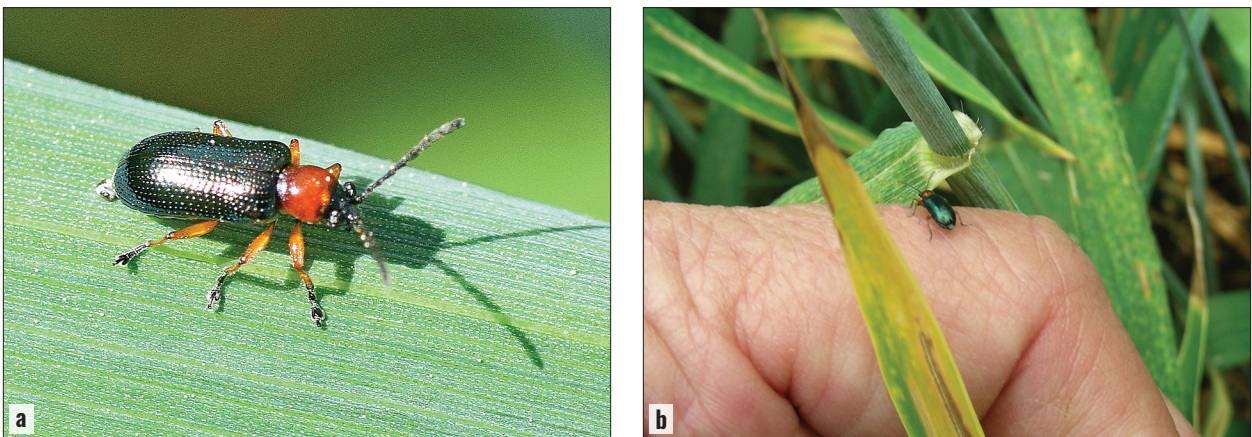


Figure 1. Adult cereal leaf beetle, *Oulema melanopus*, in wheat field (a) close-up; (b) further back for scale. (a: Kostas Zontanos, iNaturalist.org CC BY-NC 4.0; b: C. Pickett, CDFA)

took place in Indiana. Over whole regions, fields of grains and nearby suburban areas were treated with malathion and carbaryl. In 1967, after more than a million acres (>400,000 ha) of land in the Midwest had been treated with insecticides, the federal and state spray programs were abandoned; containment was deemed impossible. The California Department of Food and Agriculture imposed a quarantine against CLB during this early phase of its spread to include all states east and including Minnesota, Iowa, Missouri, Arkansas, and Louisiana (Anon., 2007).

Nature of Problem

The diet of CLB is limited to the leaves of small grains and forage grasses (Poaceae = Gramineae). It prefers oats (*Avena sativa*) over wheat (*Triticum aestivum*), barley, (*Hordeum vulgare*), or rye (*Secale cereale*) (Gallun et al., 1966). Although adults can be found feeding on grasses, it is the larval stage that causes serious economic damage (**Fig. 2a**). Larvae skeletonize and strip leaves of green tissue, and when high numbers are present, they cause fields to appear bluish (**Fig. 2b**). From 13 to 75% yield losses were reported in barley in the midwestern United States (Webster and Smith, 1979). Reduction in yield is directly related to consumption of foliage, which reduces the plant's photosynthesis (Haynes and Gage, 1981). Controlled field studies used insecticides to create pest-free fields (Buntin et al., 2004) for comparisons between fields of wheat with naturally high damage levels (>90% damaged flag leaves) and treated fields with undamaged leaves (Gallun et al., 1967). These comparisons showed a direct relationship between the number of CLB larvae on grain leaves and the degree of yield loss. Although CLB attacks many species of grasses, it prefers those with a C_3 pathway over C_4 plants (i.e., wheat over corn). Shortly after CLB was found in California, the rice industry requested studies on the potential impact of this beetle on rice, *Oryza sativa*, a C_3 plant. However, like many grasses, the crop proved to be unsuitable for CLB reproduction (Godfrey et al., 2002), suggesting there were other factors more than just C_3 vs. C_4 status that affected a grass species' suitability for this beetle.

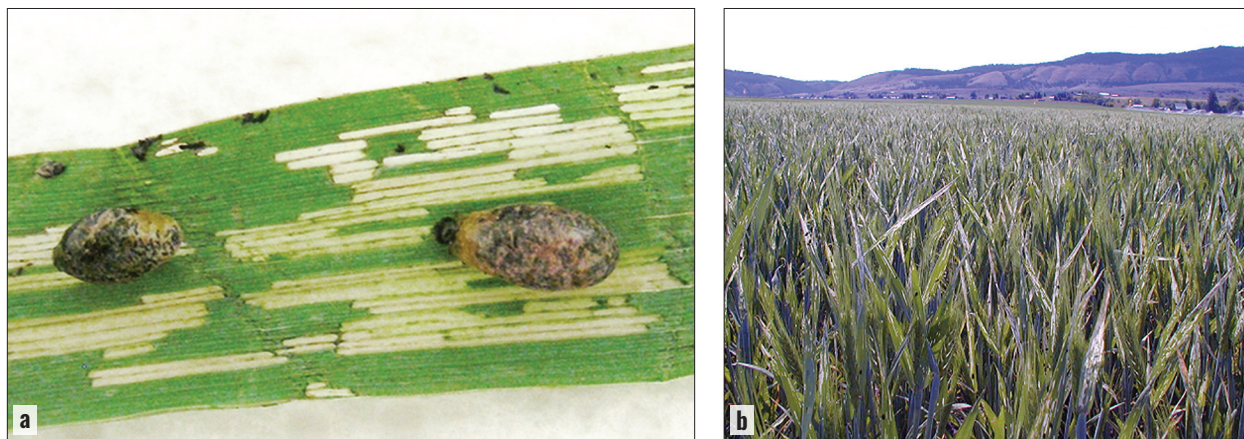


Figure 2. (a) Leaf skeletonization of oats caused by cereal leaf beetle, *Oulema melanopus* (CLB); (b) CLB-damaged wheat field. (a: Photo by C. Pickett, CDFA; b: D. Walenta, Oregon State University)

The invasion of the midwestern United States by CLB prompted the initiation of a classical biological control program against CLB. The rapid spread and increase of CLB's population demonstrated the inability of resident natural enemies to suppress its population growth, and this rapid spread triggered a regional quarantine and eradication program led by the USDA and local agencies (Haynes and Gage, 1981). As has happened with other invasions of exotic pests in the past, failed eradication efforts were followed by investment into host plant resistance, followed lastly by development of a classical biological control program. Later, when the Pacific Northwest was invaded, growers immediately started spraying on a calendar basis for CLB control. Once

chemical treatment became too costly to sustain, natural enemies of CLB were imported from midwestern states where effective CLB parasitoids had become recognized following their release in that region.

WHY CONTROL THIS INVASIVE PEST

Wheat is the most important food staple in North America and other temperate regions of the world (Shewry and Hey, 2015). Similarly, oats are also a significant grain food staple with increasing demand due to its nutritional advantages: high fiber content important for digestion and low gluten content important to patients of celiac disease (Rasane et al., 2015). Both grains are heavily attacked by CLB. Thus, there was initially a major effort to eradicate this pest from the midwestern United States. At its peak, 1,616,807 acres (654,300 ha) were being treated with insecticides in Michigan, Illinois, and Indiana. The financial cost to growers in 1966 was \$1.85 per acre (\$0.75/ha), or in total \$2,991,093 (Haynes and Gage, 1981). Adjusting for inflation, losses would be about \$30 million today (2022). Because spraying included urban areas, lawsuits arose, adding another unanticipated cost. Delineating grain fields from houses and cars was considered too expensive to do when applying pesticides aerially, and this inability to target pesticides accurately brought the eradication effort to an end. Furthermore, pesticide treatments did not slow the spread of CLB into adjoining wheat-growing states. Growers of small grains in Utah and Washington reacted in the same way following the discovery of CLB in their states (Karren, 2008; Roberts and Rao, 2012). These states immediately started massive state-coordinated, county-wide spraying for this pest, greatly increasing the growers' production costs (Roberts and Rao, 2012). Not only did these eradication projects reduce grower profits, most likely spraying disrupted natural control of other pests. As the likely failure of eradication efforts became clear to state and federal agencies funding the efforts, CLB control efforts were widened to include other management strategies. In 1963 and 1964, considerable effort was directed at developing resistant varieties of the main affected grains (wheat, oats, and barley). While some lines of wheat resistant to CLB were developed, none were found for oats. Given that CLB would likely remain a serious problem unless resistant crop varieties could be developed for all major grains, funding was finally directed at classical biological control, beginning in the early 1960s. As has happened in many past invasions, classical biological control was the 'tool' of last resort.

The most important reason for pursuing classical biological control was the need for regional control that would make a serious pest of a major food staple more manageable for growers. Although pesticides could be used, they are costly and can be disruptive to the environment. But what made this approach realistic was the discovery of several primary, larval parasitoids attacking CLB in parts of its native range in Europe. Surveys of wheat, oats, and barley measuring parasitoid prevalence, species dominance, and percent parasitism found three potential candidates for importation (Dysart et al., 1973). During nine years of surveys by the European Parasite Laboratory, USDA-ARS (currently the European Biological Control Laboratory), no serious CLB damage was recorded in grain fields in Italy, France, Spain, Denmark, or Sweden. Records summarized by others in Europe since the 1850s until 1963 reported only a few outbreaks, described as 'sporadic' and 'localized' (Dysart et al., 1973).

PROJECT HISTORY THROUGH ESTABLISHMENT

Midwestern United States

Midwestern releases

Beginning in 1965, large numbers of CLB larvae were field collected by the European Parasite Laboratory and held until parasitoid emergence. The adult parasitoids then were shipped to the

USDA-ARS laboratory in Moorestown, New Jersey. The USDA-ARS contracted with Michigan State University and Purdue University in Indiana to study the biology of these new parasitoids and to make initial releases (Maltby et al., 1971; Dysart et al., 1973; Haynes and Gage, 1981). Difficulty in rearing the larval parasitoids shifted the emphasis of the release effort towards using parasitoids reared from CLB collections in Europe for direct field releases in the United States (Dysart et al., 1973). Shipping parasitoids, primarily as diapausing larvae or pupae, provided the most vigorous parasitoids for release. The parasitoids were identified to species at the USDA-APHIS Laboratory in Niles, Michigan then shipped to cooperators. Delivery from Europe within 48 h through commercial air transportation aided rapid field release of healthy parasitoid adults. Three larval parasitoids (all Hymenoptera) were shipped for release to affected areas in eastern states from 1964 to 1971: 82,437 *Tetrastichus julis* (Eulophidae), 142,054 *Diaparsis* spp. (unknowingly a mix of two ichneumonids, *D. carinifer* and *D. temporalis*; Montgomery and De Witt, 1975; Haynes and Gage 1981), and 11,421 *Lemophagus curtus* (Ichneumonidae) (Dysart et al., 1973). During the same period, a fourth hymenopteran parasitoid, *Anaphes flavipes* (Mymaridae), was also imported from Europe. This species attacks CLB eggs (Maltby et al., 1971) and was easier to rear than the larval parasitoids. *Anaphes flavipes* was mass produced in a rearing facility built by USDA-APHIS in Niles, Michigan, starting in 1966. Nearly 300,000 egg parasitoids were reared and provided to cooperators for field releases, starting in Michigan and Indiana.

Midwestern recoveries

By 1972, all four parasitoids had been recovered from initial release locations in various states in the midwestern United States. *Tetrastichus julis*, *D. temporalis*, *L. curtus*, and *A. flavipes* were documented to have established in Michigan (Maltby et al., 1971; Dysart et al., 1973), but only *A. flavipes* was recovered in Ohio (Maltby et al., 1971). The most common larval parasitoids initially recovered in the midwestern states were *T. julis* followed by *D. temporalis*. The larval parasitoid *D. temporalis* was projected as most likely to control CLB based on its abundance in field collections in Europe, its biology, and its synchrony with CLB larvae (Dysart et al., 1973, Haynes and Gage, 1981). In 1975, *D. temporalis* was recovered from Michigan, Ohio, Indiana, West Virginia, Pennsylvania, and New York, but it hasn't been reported since then, while *L. curtus* continued to be collected, although only at low numbers. In contrast, *T. julis* was recovered with increasing frequency and at higher rates. *Tetrastichus julis* and *A. flavipes* continued to spread throughout Michigan and Ohio (Maltby et al., 1971; Dysart et al., 1973).

Western United States

Western releases

The first report of CLB in the western United States came from Utah in 1984. Despite county-wide spraying of malathion, CLB continued to spread throughout the state (Karren, 2008). In 1985, the two larval parasitoids *T. julis* and *D. temporalis*, and the egg parasitoid *A. flavipes* were imported and released into Utah (Karren, 1986) and shortly thereafter in Montana from the eastern United States, with help from USDA-APHIS (Blodgett et al., 2004). The first detections of CLB in Washington and Oregon were made in 1999. Cooperative Extension agents in these states led a coordinated survey for CLB and releases of their biocontrol agents (Rao et al., 2003; Roberts and Rao, 2012). The 'Western Cereal Leaf Beetle Team' of federal, state, and university personnel from seven states focused their efforts on establishing the parasitoids with potential to suppress CLB in the central and western United States and Canada (Logan et al., 1976; Harcourt and Guppy, 1977; Haynes and Gage, 1981; Ellis et al., 1988).

The initial releases coordinated by this western CLB team were of 13,928 *T. julis*, 25,631 *A. flavipes*, and 125 *L. curtus* from collections made in Pennsylvania and Montana (Roberts, 2016). Before being released, parasitoid shipments were examined at the Washington State University's quarantine facility. Releases were made, when possible, in field insectaries that were manipulated for high numbers of CLB in suitable stages. These insectaries were blocks of commercial or non-commercial grains grown in or near areas with high CLB density that were managed to maximize parasitoid production through high production of its host larvae, i.e., exposure to young pre-boot stage oat plants (Roberts, 2016). Sequential plantings of small grains from fall to the following spring ensured continuous presence of the optimal stage of plants for beetle development. The use of field insectaries was repeated in Oregon, but there are no published data on numbers of parasitoids released in that state. One project report (Bai et al., 2008) states that 383,626 *T. julis* and 114,160 *A. flavipes* were released from 2000 to 2008 in the northern half of Oregon. In 2013, CLB was reported for the first time in California. Most likely this was at the very early stage of the beetle's invasion into California given that 10 years of state-wide surveys by the California Department of Food and Agriculture (2001-2010) did not report any CLB adults (Dowell and Pickett, 2016). In 2014, one year after the 2013 CLB detection), a total of 630 *T. julis* parasitoids were collected from wheat fields near Portland, Oregon and released into northern California at an insectary following methods described in Roberts (2016) and managed by the UC Intermountain Research and Extension Center at Tulelake (Pickett et al., 2021). From 2015 to 2017, six releases of *T. julis* (from a low of 20 up to 530 individuals each) were made in commercial wheat fields using CLB larvae from this field station. Parasitoids were released as larvae inside their CLB hosts (Fig. 3); numbers of parasitoids were estimated for each release by dissecting 5–10 hosts to check for parasitism.



Figure 3. Parasitoid-filled cadaver of cereal leaf beetle, *Oulema melanopus*, showing emerging *Tetrastichus julis* larva, circled in red. (C. Pickett, CDFA)

Western recoveries

In Utah, only *T. julis* established permanent populations (Karren, 2008). In Washington and Oregon, *A. flavipes*, although released in large numbers, did not establish (Roberts, 2016). Similarly, *L. curtus* has not yet been reported as established in Washington, following releases of small numbers. In northern California, parasitism of CLB by *T. julis* reached 80% at the field insectary one year after initial releases (Pickett et al., 2021). Pre-release dissections at the same site showed *T. julis* was present but at low densities when parasitoids were first released. Interestingly, Roberts (2016) also reported 80% parasitism at one of their insectaries in Washington one year following releases, and they speculated, without data, that the parasitoid was already present at the time of initial releases. These results, and the discovery of *T. julis* outside of field insectaries in Washington and California (Roberts, 2016; Pickett et al., 2021) suggest this parasitoid was able to rapidly disperse and track populations of CLB invading new areas. Contrary to earlier studies on *T. julis* (Haynes and Gate, 1981), this species rapidly spread through the Pacific Northwest and dispersed into both crop and non-crop habitats (Evans et al., 2015).

One caveat: the lack of recoveries of some parasitoid species that were released may not reflect their absence so much as the little effort expended in looking for them. They may be present on other non-target species or just present in very low numbers on CLB.

HOW WELL DID IT WORK?

Impact in the Midwestern United States

For the midwestern United States, little quantitative information on the impact of the project on CLB densities was recorded because few long-term post-release studies were carried out documenting parasitism and changes in CLB numbers. We do know that *T. julis* was repeatedly recovered from CLB larvae within just a few years of its release at the Kellogg Biological Station in Michigan, and parasitism there went from 20% in 1975 to 60% the following year. A parallel decline in the local CLB population also occurred in the same period at a site in Jackson County that was nearly 47 mi (75 km) away, where parasitoids had not been released. This decline led to the belief that causes other than parasitism were responsible (Haynes and Gage, 1981). However, because other releases of *T. julis* had been made in 1965 at sites near the USDA-APHIS rearing facility in Niles, Michigan (about 62 mi or 100 km from the Jackson County site), it is possible that the parasitoid had dispersed on its own to Jackson County by the mid-1970s. In 1975 there was little evidence that *T. julis* alone could have such a large impact on CLB, and expectations for its success at that time were low because *T. julis* was considered a poor disperser and possibly a poor competitor with *A. flavipes*, which at that time seemed more promising. Also, predictions of impact needed to consider an important difference between Europe and North America, which was that the introduced primary parasitoids were freed of any restraints imposed on them by their co-evolved, secondary parasitoids. Dysart et al. (1973) recorded three hyperparasitoids collected from *Oulema* spp. (CLB and its relatives) in Europe, any of which could have affected the impact of the primary parasitoids if present in the United States. To date, however, there have been no reports of hyperparasitism of the introduced CLB parasitoids in the United States.

Impact in the Pacific Northwest

More recently, in the Pacific Northwest the primary goal of the CLB team was to establish field insectaries for *T. julis* to support widespread releases. No effort was made to measure CLB numbers before and after releases, only their parasitism shortly after releases were made. In Washington State, Roberts (2016) provided detailed estimates of parasitism at several field insectaries. Where measurements were made over 2 to 4 years, the annual trends in parasitism were always upward, going from a low of 11% to a high of 100%. For seven locations, the average parasitism of CLB larvae in the final year of observations was 90%. Although a similar effort was not made in Oregon by Cooperative Extension, the USDA-APHIS did report on the change in acreage of cereals treated with pesticides for CLB, as well as the cost of pesticide treatment in that state (Roberts and Rao, 2012). In 2004, at CLB's peak density in Oregon, 64,200 acres (25,980 ha) were treated with insecticides at a total cost of \$770,400. By 2007, three years after the start of releases of *T. julis*, the acreage treated had dropped by 70% to 19,141 ac (7,746 ha).

Impact in Northern California

In northern California, the impact of *T. julis* on CLB was measured at the initial field insectary located at the UC Intermountain Research and Extension Center in Tulelake from 2016 to 2019 and in several commercial wheat fields in the Klamath Basin wheat-growing area in northern California on the Oregon border (Pickett et al., 2021). The insectary in Tulelake consisted of a sequence of plots planted first to wheat in the fall followed

by three adjacent plots of oats seeded about 3–4 weeks apart beginning the following April. The result was an insectary that started with young winter wheat followed by the continuous presence of early-stage oats. The undisturbed, non-sprayed plot of wheat was meant to attract the fall cohort of CLB adults and provide a bridge to young host plants for CLB and parasitoids the next year. This sequence of plantings was maintained for five years. Parasitism was based on samples taken one to two weeks apart, usually June through July, pooling on each sample date the larvae collected from all plots of oats at the UC Intermountain Research and Extension Center CLB insectary. Parasitism was measured by dissecting 2nd to 4th instar CLB larvae and recording the number of beetle larvae found with eggs or developing larvae of *T. julis*. Annual parasitism, based on the proportion of CLB larvae parasitized on each date and averaged over the summer at this insectary location, increased from 59% in 2016 (two years after releases), to 73% in 2017, and 85% in 2018. Oats were used as the host plant in these plots because of CLB's preference for this plant over other common grains (Gallun et al., 1966; Wellso and Hoxie, 1988; Roberts and Walenta, 2012).

Because parasitism reached such high levels so quickly, high numbers of CLB larvae, parasitized or otherwise, were rarely observed. Nevertheless, the UC Intermountain Research and Extension Center insectary in Tulelake was a source for naturally dispersing parasitoids in this region and for parasitized larvae that were deliberately released into nearby fields. Over several years, commercial fields of small grains in the region, located within 18.6 mi (30 km) of the field insectary at the UC Intermountain Research and Extension Center, showed a decline in numbers of CLB while parasitism was increasing (Fig. 4) (Pickett et al., 2021). The combined number of CLB nymphs and adults in this region was reduced by nearly 90% over the same four years (2016–2019). These fields were all located within a 25 x 25 mi (40 x 40 km) region, and the sampling results showed that *T. julis* could move several miles a year and rapidly increase its population numbers, a result that was also corroborated by Evans et al. (2015). Based on our own estimates, *T. julis* could successfully lay about six eggs per beetle larva, in agreement with other similar studies (Dysart et al., 1973). Because *T. julis* has two generations per year compared to just one for CLB, and the parasitoid can quickly move into new fields in search of hosts, it is reasonable that it can suppress beetle populations as rapidly as in a single year.

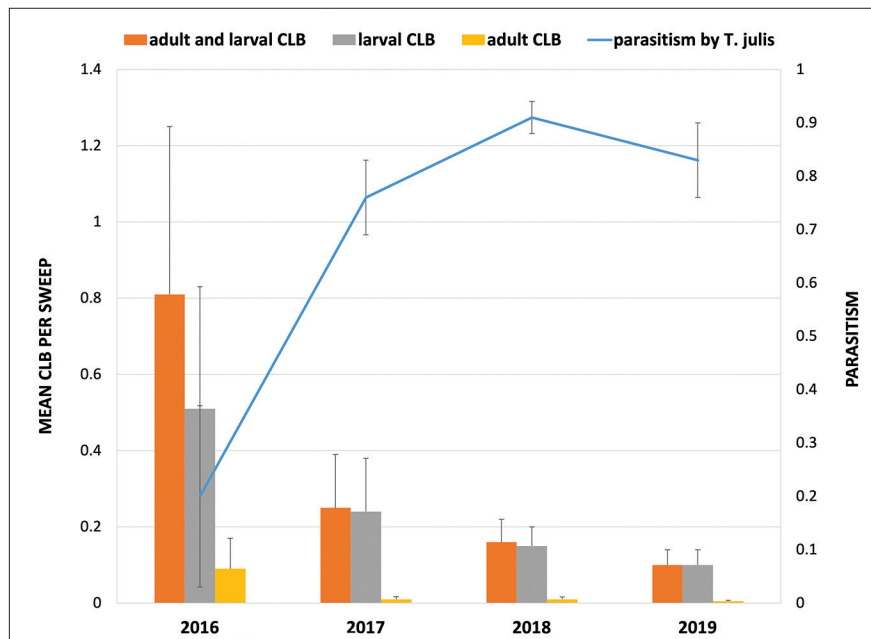


Figure 4. Changes in cereal leaf beetle, *Oulema melanopus* (CLB), numbers and portion parasitized by *Tetrastichus julis* in Modoc County, California 2016–2019. (modified from Pickett et al., 2021)

Effects on Non-Target Insects

In the 1960s, when the biological control project against CLB was started in Michigan, studies of possible impacts on non-target insects were not required by the federal government. However, in the early 2000s, post-release tests were carried out in Canada to detect potential non-target impacts (Hervet et al., 2016). Six species of beetles that were taxonomically related to CLB and shared similar life history traits were chosen from the beetle community of southern Alberta where *T. julis* had recently become established. In no-choice tests, none of these six beetle's larvae were attacked by *T. julis*, but some CLB larvae were parasitized, providing strong evidence this parasitoid is highly specialized to reproduce on CLB. Thus, work of earlier researchers who followed the standard protocols used for foreign exploration and selection of natural enemies for release in the 1960s, resulted in the establishment of an effective and safe parasitoid. In many areas of the country, *T. julis* is now highly effective in reducing populations of CLB in ephemeral grain crops. At the same time, it is highly selective as to which host species it uses for reproduction. To our knowledge, similar host specificity studies were never carried out for *A. flavipes*, the only other biocontrol agent known to widely establish permanent populations in the United States.

In our study (Pickett et al., 2021), as well as in work by Evans et al. (2013), *T. julis* populations were well synchronized with CLB during this parasitoid's first generation but not the second, resulting in a dip in parasitism levels in mid-summer. This has been attributed to increasing spring temperatures and a phenological mismatch between CLB and the parasitoid (Evans et al., 2013). Nevertheless *T. julis* has still been able to maintain high average seasonal parasitism of CLB (Roberts, 2016; Pickett et al., 2021) in the Pacific Northwest. Most likely various predators, as observed in our studies, and in laboratory and field studies by others (Shade et al., 1970; Kheirodin et al., 2019), also help control CLB in many parts of North America.

BENEFITS OF BIOLOGICAL CONTROL OF CEREAL LEAF BEETLE

The best data on the economic impact of the CLB project come from the survey by Cooperative Extension and the USDA-APHIS in Oregon. In that state, the cost of pesticides used to control CLB in Oregon, when they were causing the greatest concern in 2004, was nearly \$800,000 statewide (Roberts and Rao, 2012). This information implies that in the absence of the successful CLB biocontrol program, the cost of chemical control would have amounted to nearly \$16 million in just one state (in 2004 dollars) by 2022. In addition, the alternative to biological control, the annual use of insecticides to control CLB, would have resulted in unknown but likely substantial non-target effects to insects and the environment.

In the state of Washington, Roberts (2016) calculated the savings to wheat farmers attributable to the parasitoid's establishment and reduction of CLB populations. Considering application and pesticide expenditures in 2009, CLB control cost \$13/acre (\$33/ha). Using National Agricultural Services data, Roberts (2016) determined that if only half the wheat acreage in Washington were treated, it would cost \$3.3 million annually. Again, the repeated savings of this amount annually would result in over \$30 million per decade, in addition to reduced impact on the environment through the lack of these widespread annual pesticide applications.

Although this biological control effort has greatly benefited the producers of small grains in the Midwest, Pacific Northwest, and California, the same may not be true everywhere *T. julis* has spread in the United States. For example, a review of the CLB problem in the southeastern United States found little evidence for suppression of CLB by this parasitoid (Philips et al., 2011). This conclusion may be due to the lack of survey effort for *T. julis* in the region and the general reliance by growers on calendar-based pesticide schedules for CLB, rather than actual demonstrated need in particular fields.

ACKNOWLEDGMENTS

We gladly thank Ted Evans for increasing our understanding of the biology of *Tetrastichus julis*. The USDA-ARS European Biological Control Laboratory is to be credited for the initial discovery and importation of parasitoids for the control of cereal leaf beetle, especially *T. julis*. We thank Rob Wilson and the University of California Research and Extension Center in Tulelake for providing plots of small grains for our insectary. Marypat Stadtherr, Viola Popescu, and Chris Borkent all contributed to the information in this chapter originating from CDFAs role in biological control of cereal leaf beetle in California.

REFERENCES

- Anon. 2007. California Code of Regulations, Title 3.
- Bai, B. B., R. A. Worth, H. W. Rogg, and G. Brown. 2008. Cereal Leaf Beetle Biological Control Program in Oregon, 2008. <https://hdl.handle.net/2376/2247>
- Blodgett, S., C. I. Tharp, and K. Kephart. 2004. Cereal leaf beetle. Montana State University Extension Publication MT200406AG.
- Buntin, G. D., K. L. Flanders, R. W. Slaughter, and Z. D. DeLamar. 2004. Damage loss assessment and control of the cereal leaf beetle (Coleoptera: Chrysomelidae) in winter wheat. *Journal of Economic Entomology* 97(2): 374–382.
- Dowell, R. V. and C. H. Pickett. 2016. The cereal leaf beetle, *Oulema melanopus* Linnaeus, 1758 (Coleoptera: Chrysomelidae) in California: detection and response. *The Pan-Pacific Entomologist* 92(3): 165–167.
- Dysart, R. J., H. L. Maltby, and M. H. Brunson. 1973. Larval parasites of *Oulema melanopus* in Europe and their colonization in the United States. *Entomophaga* 18(2): 133–167.
- Ellis, C. R., B. Kormos, and J. C. Guppy. 1988. Absence of parasitism in an outbreak of the cereal leaf beetle, *Oulema melanopus* (Coleoptera: Chrysomelidae), in the central tobacco growing area of Ontario. *Proceedings of the Entomological Society of Ontario* 119: 43–46.
- Evans, E. W., J. B. Karren, and C. E. Israelsen. 2006. Interactions over time between cereal leaf beetle (Coleoptera: Chrysomelidae) and larval parasitoid *Tetrastichus julis* (Hymenoptera: Eulophidae) in Utah. *Journal of Economic Entomology* 99(6): 1967–1973.
- Evans, E. W., V. L. J. Bolshakova, and N. R. Carlile. 2015. Parasitoid dispersal and colonization lag in disturbed habitats: biological control of cereal leaf beetle metapopulations. *Journal of Applied Entomology* 139: 529–538. <https://doi.org/10.1111/jen.12191>
- Evans, E. W., N. R. Carlile, N. R., M. B. Innes, and N. Pitigala. 2013. Warm springs reduce parasitism of the cereal leaf beetle through phenological mismatch. *Journal of Applied Entomology* 137(5): 383–391. <https://doi.org/10.1111/jen.12028>
- Gallun, R. L., R. T. Everly, and W. T. Yamazaki. 1967. Yield and milling quality of Monon wheat damaged by feeding of cereal leaf beetle. *Journal Economic Entomology* 60(2): 356–359.
- Gallun, R. L., R. Ruppel, and E. H. Everson. 1966. Resistance of small grains to the cereal leaf beetle. *Journal of Economic Entomology* 59(4): 827–829.
- Godfrey, K., S. Blodgett, and P. Denke. 2002. Susceptibility of rice and wild rice to the cereal leaf beetle, pp 10–11. In: Woods, D. M. (ed.). *Biological Control Program Annual Summary, 2001*. California Department of Food and Agriculture, Plant Health and Pest Prevention Services, Sacramento, California.
- Harcourt, D. G., J. C. Guppy, and C. R. Ellis. 1977. Establishment and spread of *Tetrastichus julis* (Hymenoptera: Eulophidae), a parasitoid of the cereal leaf beetle in Ontario. *Canadian Entomologist* 109: 473–476.
- Haynes, D. L. and S. H. Gage. 1981. The cereal leaf beetle in North America. *Annual Review of Entomology* 26: 259–287.
- Hervet, V. A. D., H. A. Cárcamo, L. M. Dodsall, T. D. Miller, and S. V. Kher. 2016. Assessment of potential non-target effects of *Tetrastichus julis*, a biological control agent of the cereal leaf beetle, *Oulema melanopus*. *BioControl* 61: 399–411.
- Karren, J. B. 2008. Summary of Utah CLB biocontrol efforts. Utah Collection, Cereal Leaf Beetle Research - Western North America. Washington State University Libraries Exchange, Pullman, Washington. <https://research.libraries.wsu.edu/xmlui/handle/2376/1928>

- Kher, S. V., L. M. Dossdall, and H. Cárcamo. 2013. *Oulema melanopus* (L.), cereal leaf beetle (Coleoptera: Chrysomelidae), 233–237. In: Mason, P. G. and D. R. Gillespie (eds.). *Biological Control Programmes in Canada 2001–2012*. CAB International, Wallingford, U.K.
- Kheirodin, A., A. C., Costamagna, and H. A. Cárcamo. 2019. Laboratory and field tests of predation on the cereal leaf beetle, *Oulema melanopus* (Coleoptera: Chrysomelidae). *Biocontrol Science and Technology* 29(5): 451–465. <https://doi.org/10.1080/09583157.2019.1566437>
- Logan, P. A., F. W. Stehr, and R. J. Sauer. 1976. The subcolonization and buildup of *Tetrastichus julis*, (Hymenoptera: Eulophidae) a larval parasitoid of the cereal leaf beetle, (Coleoptera: Chrysomelidae) in the Lower Peninsula of Michigan. *The Great Lakes Entomologist* 9(1): 1–4.
- Maltby, H. I., F. W. Stehr, R. C. Anderson, G. E. Moorehead, L. C. Barton, and J. D. Paschke. 1971. Establishment in the United States of *Anaphes flavipes*, an egg parasite of the cereal leaf beetle. *Journal of Economic Entomology* 64: 693–697.
- Montgomery, V. E. and P. R. DeWitt. 1975. Morphological differences among immature stages of three genera of exotic larval parasitoids attacking the cereal leaf beetle in the United States. *Annals of the Entomological Society of America* 68(3): 574–578.
- Philips, C. R., D. A. Herbert, T. P. Kuhar, D. D. Reising, W. E. Thomason, and S. Malone. 2011. Fifty years of cereal leaf beetle in the U.S.: An update on its biology, management, and current research. *Journal of Integrated Pest Management* 2(1): C1–C5. <https://doi.org/10.1603/IPM11014>
- Pickett, C. H., C. J. Borkent, R. Wilson, M. Stadtherr and, V. Popescu. 2021. Introduction of the cereal leaf beetle parasitoid *Tetrastichus julis* (Hymenoptera: Eulophidae) into California. *Biocontrol Science and Technology* 32(1): 1–13. <https://doi.org/10.1080/09583157.2021.1933901>
- Rao, S., A. A. Cossé, R. J. Bartelt, and B. W. Zilkowski. 2003. Aggregation pheromone of the cereal leaf beetle: field evaluation and emission rates. *Journal of Chemical Ecology* 29: 2165–2175.
- Rasane, P., A. Jha, L. Sabikhi, A. Kumar, and V. S. Unnikrishnan. 2015. Nutritional advantages of oats and opportunities for its processing as value added foods – a review. *Journal of Food Science and Technology* 52(2): 662–675. <https://doi.org/10.1007/s13197-013-1072-1>
- Roberts, D. E. 2016. Classical biological control of the cereal leaf beetle, *Oulema melanopus* (Coleoptera: Chrysomelidae), in Washington State and role of field insectaries, a review. *Biocontrol Science and Technology* 26(7): 877–893. <https://doi.org/10.1080/09583157.2016.1165794>
- Roberts, D. and S. Rao. 2012. Extension leads multi-agency team in suppressing a pest in the west. *Journal of Extension* 50(2), Article #66. <https://tigerprints.clemson.edu/joe/vol50/iss2/66>
- Roberts, D. and D. L. Walenta. 2012. Integrated pest Management (IPM) for the Cereal Leaf Beetle in Washington State. Washington State University Extension, EM054E.
- Shade, R. E., H. L. Hansen, and M. C. Wilson. 1970. A partial life table of the cereal leaf beetle, *Oulema melanopus*, in northern Indiana. *Annals of the Entomological Society of America* 63(1): 52–59.
- Shewry, P. R. and S. J. Hey. 2015. The contribution of wheat to human diet and health. *Food Energy and Security* 4(3): 178–202. <https://doi.org/10.1002/fes3.64>
- Webster, J. A. and D. H. Smith. 1979. Yield losses and host selection of cereal leaf beetles in resistant and susceptible spring barley. *Crop Science* 19(6): 901–904.
- Wellso S.G. and R.P. Hoxie. 1988. Biology of *Oulema*. In: Jolivet, P., E. Petitpierre, and T.H. Hsiao (eds.). *Biology of Chrysomelidae. Series Entomologica, Vol 42*. Springer, Dordrecht, Netherlands.