PS&C
Prairie Soils &
Crops Journal

The Cereal Leaf Beetle: Biology, Distribution and Prospects for Control

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Summary
The cereal leaf beetle is an invasive Eurasian pest of cereals including wheat, oats and barley recently discovered in western Canada. It has been established in North America at least since 1962, and since then it has expanded its geographical range significantly. Management approaches include quarantine, insecticides, cultural control, plant resistance, and biological control. However, biological control with natural enemies has been the most successful strategy for control in North America following the successful establishment of its principal parasitoid, *Tetrastichus julis* introduced from Europe. This paper presents an overview of the distribution and invasion of cereal leaf beetle in North America, its life history and control strategies. Prospects for its control in western Canada are also addressed.

Introduction
The cereal leaf beetle, *Oulema melanopus* L. (Coleoptera: Chrysomelidae), is a relatively recent alien invasive pest in western Canada that infests a range of agriculturally important cereal crops including wheat, oat and barley[1,2]. Native to Eurasia the cereal leaf beetle is a common pest of cereals throughout Europe and particularly in the Balkan region[3]. The beetle was discovered in North America in 1962 in Michigan, U.S.A.[4,5,6]. Its exact portal and mode of entry into North America are unknown but it may have arrived in straw material from Europe[7,6]. The beetle has expanded its range in recent years to encompass most regions of cereal production in the U.S.A.[8,9], and portions of Alberta, Saskatchewan and Manitoba[10,11].

Western Canada is the major cereal grain production region of Canada[12], and provides a favourable climate for population expansion of the cereal leaf beetle. It lacks geographic or ecological barriers to prevent further dispersal, and provides a diverse host plant range that can enhance the ability of the species to spread and establish in new sites[13,10]. Climate change may also affect the future distribution of the beetle and prediction models based on current conditions and different incremental temperature scenarios suggest that the insect could expand its geographic range across the entire cereal-growing region of Canada[14,15]. Establishment of this pest thus has several economic implications for grain production, trade and export and presents a potential threat to cereal production in western Canada; consequently there is an urgent need to understand its local biology, ecology and prospects for integrated management.

Cereal Leaf Beetle Distribution and Range Expansion
In Europe, crop monoculture practices and intensification of food production following industrialization of the food sector have contributed significantly to the increasing abundance of the cereal leaf beetle[16,17]. It is a significant pest in Hungary[18,19], Poland[17], Moldova[20], Russia[21], Bulgaria[3], Serbia[22,23], The Netherlands[24], Belgium and France[25], Germany[26], and Italy[27], and was also reported in India[28], Pakistan[29] and Iran[30].

Following its arrival in the north-central U.S.A. in 1962, the cereal leaf beetle quickly spread throughout the region[31,7,32,33]. The insect was reported in southern Ontario in 1965[34,6], in the Maritime Provinces in 1994[6], in the Creston Valley of British Columbia in 1998[35], and more recently in Alberta (2005), Saskatchewan (2008) and Manitoba (2009). Surveys indicate an increase in its range and abundance since 2006[11] (Fig. 1).

Fig.1. Geographic expansion of *O. melanopus* in western Canada

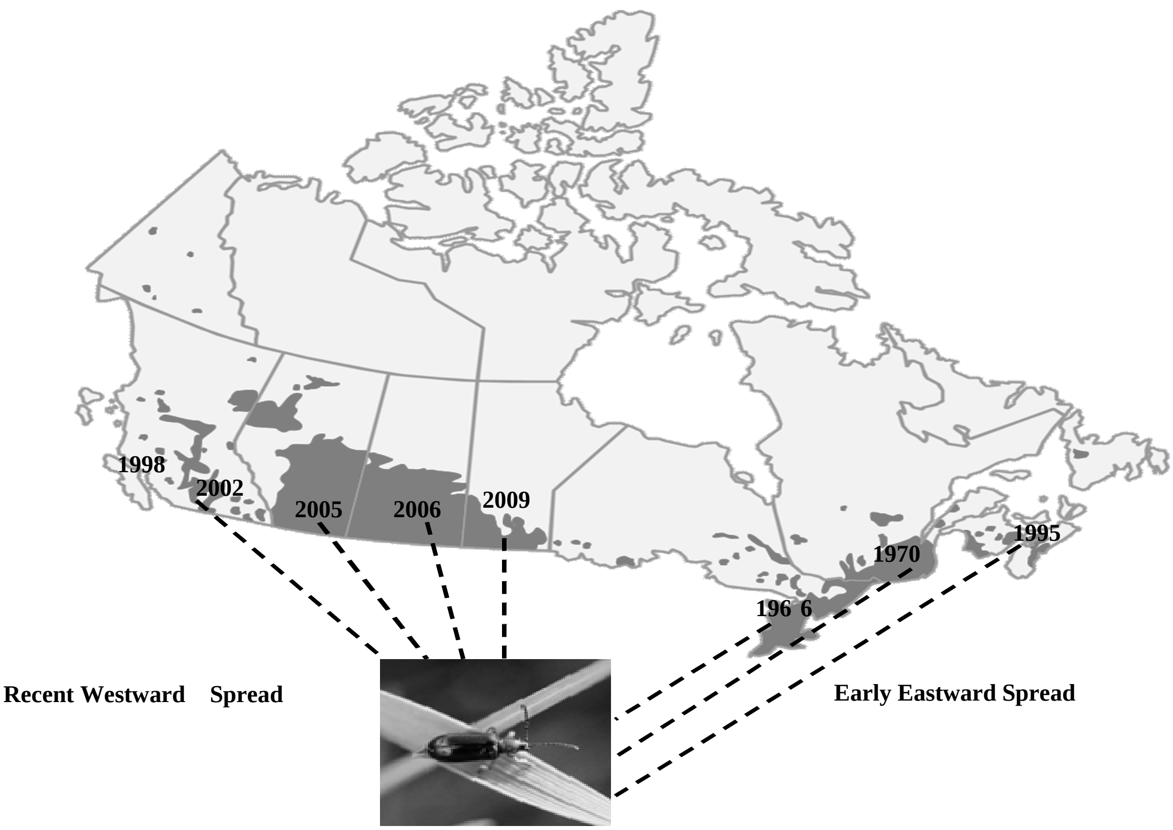

Illustration: Swaroop Kher (Source: Kher, unpublished data)
Photo: Cereal leaf beetle: Dr. L. M. Dosdall

Cereal Leaf Beetle Life History and Field Dynamics

The biology and field dynamics of the cereal leaf beetle have been well studied and documented across different regions in the world including southern Alberta. The phenology and host adaptability of the beetle differ from region to region. In general, the beetle is active from mid-March to July. Peak oviposition occurs in late March to early April when succulent hosts become available[36,37]. Eggs are laid on the upper surfaces of leaves along the margins or close to the leaf mid-rib[16]. Oats and barley are favoured for oviposition whereas pubescent varieties of wheat are least preferred[38]. Female fecundity and oviposition behaviour are determined by a variety of factors including plant nutrition, host morphology, and other micro-climatic factors. Adult host feeding before and during oviposition greatly influences the rate of oviposition[37]. Eggs are laid preferentially on central upper leaf surfaces on barley and wheat and on the central to basal region on oats. Leaf width influences the rate of oviposition. Sunlight and light intensities orient female beetles for oviposition[39]. Eggs are laid singly or in multiple clusters of two or three eggs touching end to end[32]. The eggs hatch in about four to six days and the most favourable developmental temperature is about 21^{o}C[40]. Each female lays about 50 to 275 eggs[26]. There are four larval instars and larvae tend to feed mainly on upper leaf surfaces between veins[41]. Larvae in the field are smeared with a fecal coat during feeding which eventually is lost with the formation of the prepupa[42]. Larvae are more damaging than adults and have been reported to consume plant biomass one to 10 times their body weight[20]. The fourth-instar larva is photopositive, globose and has a characteristic fecal coat. It then enters a prepupal stage before forming pupa. The prepupa is elongate, lacks a fecal coat, and secrets adhesive material to form a cocoon using earthen material[37]. Prepupae of the cereal leaf beetle enter the soil at the base of the host plant and form pupal cases near the roots at a preferred depth of about 5 cm[4]. High temperatures negatively affect pre-pupae while variations in humidity are undesirable for adults[43]. First-generation adults emerge in about three weeks and feed on various grasses before overwintering until March-April[44]. Preferred overwintering sites include edges of crops and woodlots, fence rows, sparse woods and dense woods[45]. However, the beetles prefer field debris, crevices of bark and rolled leaves for overwintering[16,17]. The cereal leaf beetle has a single generation per year[37]. Factors such as late planting, lack of nitrogen fertilization and poor quality of soil can reduce field populations of the cereal leaf beetle[46]. In southern Alberta, beetle activity in the field begins from mid-April to May with the emergence of overwintered adults (Kher, unpublished data). Adults disperse to winter wheat fields, mate and begin ovipositing. Peak oviposition occurs in May. Larvae are active from May until July. Larvae are less mobile and do not usually move from one plant to another. Pupation occurs beneath the soil in July and new generation adults emerge in about three weeks. The adults feed for a short time on crop plants in late summer before dispersing to overwintering sites. Greater infestation levels have been observed in winter wheat than in spring cereals including spring wheat, oat and barley (Kher, unpublished data). (Fig. 2)

Fig 2. Phenology of the cereal leaf beetle in southern Alberta

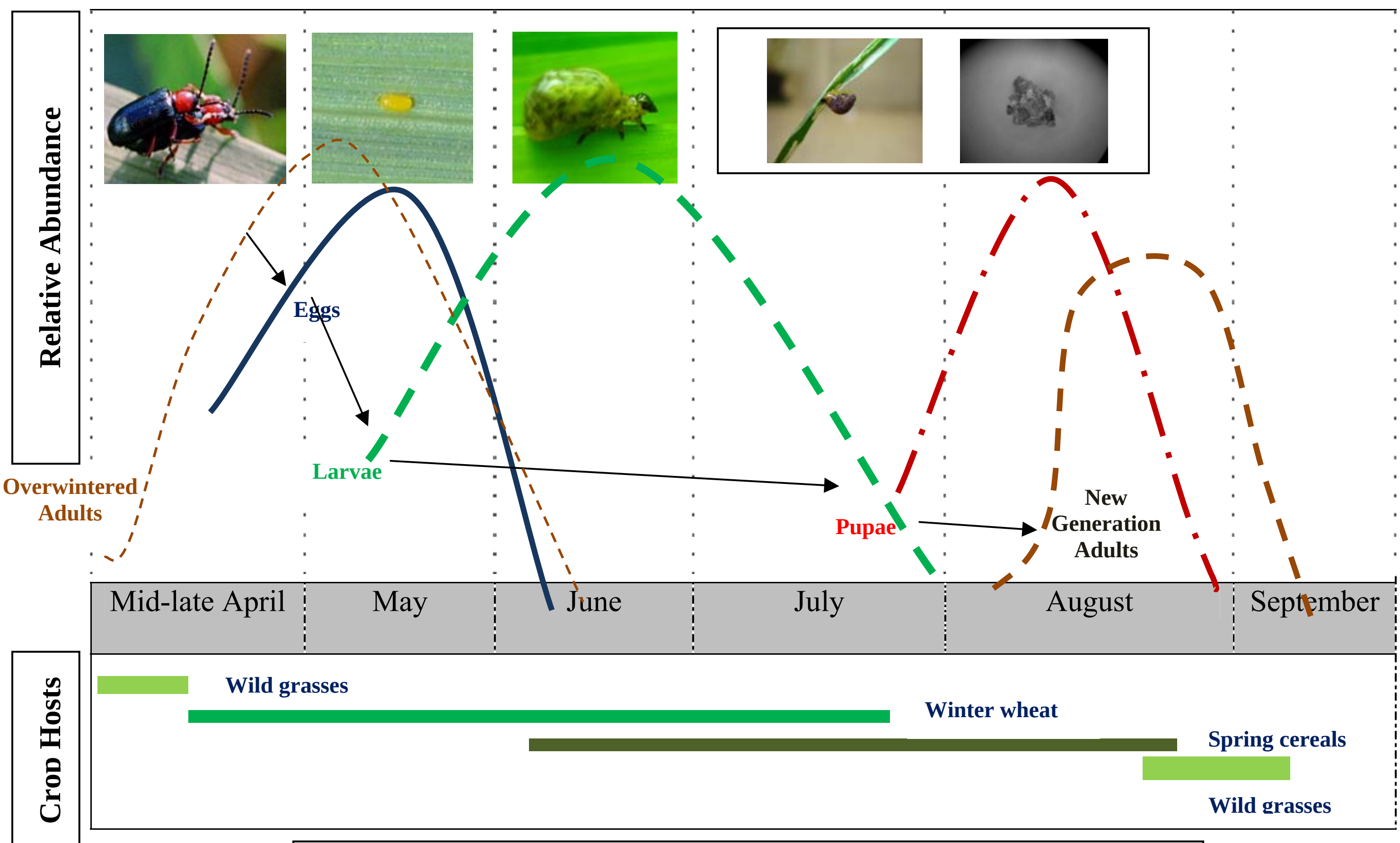

Illustration and Photos: Swaroop Kher (Source: Kher, unpublished data)
Photo: Mating Cereal Leaf Beetle Adults on leaves by Dr. L. M. Dosdall

Host Range and Damage Potential

The cereal leaf beetle attacks many wild and domesticated grasses[31]. Although considered polyphagous within the family[47], the insect prefers: wheat, oat, barley > rye, timothy > fescue > grain sorghum, corn. The species does not survive on Sudan grass, green foxtail, or wild cane[48]. Varied host preferences across different geographical regions have been observed. For example, the insect showed a preference for oat over barley and spring triticale in Poland[16], for corn in Hungary[19], and for soft red winter wheat and spring oats in some parts of the U.S.A.[49]. Larval feeding leads to significant losses in crop yield quantity and quality due to reduced photosynthetic activity[7,44,3].

Most crop damage is caused by the late larval instars with the fourth instar alone responsible for about 70% of all damage. Feeding at the flag leaf stage is most damaging to crop yield[50]. Adult feeding is characterized by uniform longitudinal incisions[51]. Wheat seedlings are most prone to the attack by both larvae and adults[48]. Grain yield reductions primarily from flag leaf damage in Europe ranged from 3 to 8% in Poland[17] to 95% in The Netherlands[24] and 70% in central Europe[25,23]. In North America, yield losses of 55% in spring wheat, 23% in winter wheat, and 38 to 75% in oat and barley have been documented due to cereal leaf beetle infestations[52,53]. In Canada, yield losses may reach 30%[10].

Controlling the Cereal Leaf Beetle: Overview of Control Strategies

Tactics for controlling *O. melanopus* in North America include quarantine, chemical control, cultural control, plant resistance, and classical biological control using its native natural enemies from Europe[54]. Attempts to sterilize males with radiation were not successful due to high mortality from the irradiation and low beetle survival on artificial media. No effective attractants are known[7].

Chemical Control. Control initially relied heavily on the use of insecticides[55] which included compounds like carbofuran (soil application) and endosulfan (foliar sprays)[56,57]. Synthetic pyrethroids such as permethrin, cypermethrin and fenvalerate were effective at low doses and were biodegraded by the plant, but were found to be lethal to the natural enemies of the pest, mainly the parasitoid wasp, *Tetrastichus julis* (Walker) (Hymenoptera: Eulophidae)[58]. Use of chemicals may adversely affect the survival and development of natural enemies thus hampering the process of natural control of the pest which might favour pest outbreaks. Seed treatment in barley with imidacloprid caused about 40% mortality, while foliar sprays caused about 90% mortality in the cereal leaf beetle population[59].

Cultural Control. Lower seeding rates in oats to mitigate cereal leaf beetle attack have been successful in some regions on a limited scale[54]. This might be due in part to the resultant sparse crop stand, the capacity of oats to compensate for beetle damage, and differences between temperature thresholds of oats and the beetle. In colder growing seasons, oats can develop well and compensate for any damage even at low temperatures between 3 to 4^{o}C while the temperature threshold for the beetle is about 9^{o}C. This difference favours oats over the pest. Sparse crop stands result in fewer eggs and larvae and thus less damage. However, due to limited success of this approach it is generally not recommended to seed at lower rates than recommended[54]. Mixed cropping of oats with barley in Poland lowered yield losses by about 9% in oats by providing the opportunity for complementary feeding by the pest while the host plant compensated for the damage[16]. Plant nutrition and judicious fertilizer use also affect pest development. A combination of nitrogen and potassium fertilizers in spring wheat proved effective against the pest. Nitrogen contributed to high crop vigour while potassium induced early crop maturity before the larvae had attained their peak activity. Potassium also imparted unpalatability to host plants that reduced pest damage[22].

Host Plant Resistance. Trichomes or pubescence (plant hairs) deter feeding, oviposition or both, resulting in "non-preference" [60]. Mechanisms of resistance in wheat have been widely explored[61,38,62,41,63] and wheat demonstrates strong resistance mechanisms compared to oat and barley[64]. Leaf pubescence in wheat can deter oviposition and affects hatchability, larval survival and adult feeding on resistant wheat varieties[38,42,65,66]. The source of resistant germplasm for the cereal leaf beetle is concentrated mainly in Asia Minor and south-eastern Europe[62,64] and initial efforts to control the pest focused on exploration of resistant germplasm in small grain host crops[64], such as wheat[38,42], and barley[64]. Trichomes of pubescent wheat varieties contain silica which imparts indigestibility[37]. Narrow-leaved cereal varieties also resist larval feeding by limiting the space for feeding and larval activity[67]. Production of volatile compounds by some host species also has antibiotic effects on the larva. For example, a secondary volatile chemical, 2,4-dihydroxy-7-methoxy-1,4-benzoxazin-3-one (also called DIMBOA), in corn negatively affects the growth of overwintered adults[68]. Some important constraints in exploiting resistant germplasm for cereal leaf beetle control include difficulties in locating resistant sources, low success with crossing, narrow adaptation and more importantly, the association of resistance with lower yields[3]. Nonetheless, host plant resistance deserves consideration as a component of integrated pest management.

Biological Control. Biological control with introduced natural enemies has been the most successful strategy for managing the cereal leaf beetle[69]. The fauna of natural enemies of the cereal leaf beetle includes insect predators, parasitoids, mites and some bird species[26]. The species of larval parasitoids introduced for biological control include *T. julis*, *Diaparsis carinifer* (Thomson) and *Lemophagus curtus* (Townes) (Hymenoptera: Ichneumonidae), and an egg parasitoid, *Anaphes flavipes* (Foerster) (Hymenoptera: Mymaridae)[7,6]. Mass multiplication of *T. julis* in the laboratory for field release is difficult due to limited success in parasitoid reproduction and development[4]. This gave rise to the successful concept of "field nurseries" in which the parasitoids are reared in a protected field area with deliberate cereal leaf beetle infestations to support parasitoid growth under natural conditions; parasitized larvae are relocated to infested fields[4,70,71]. *T. julis* remains the most successful parasitoid of the cereal leaf beetle and the wasp is well established in North America due to its high synchronization with the host and capacity to track its host as the host range expands geographically[7]. *Tetrastichus julis* is a host-specific, bivoltine, gregarious larval endoparasitoid of the cereal leaf beetle[4,7,5]. The parasitoid lays about four to six eggs per host larva and attacks all instars, but the young larvae are preferred[4]. It overwinters in the larval stage within the pupal cell of its host at a soil depth of 5 cm[1]. Overwintered females parasitize mostly early developing beetle larvae at the beginning of the season[5]. The parasitized host larva dies after pupation[4,72]. Parasitization is high in spring with a peak in mid-May to June. However, the second generation of adults also parasitizes late-maturing host larvae[4,7,73]. *Tetrastichus julis* is equally active in oat, wheat and barley[5]. High temperatures during mid-June can induce a period of quiescence (called diapause) until favourable temperatures return[74]. In eastern Canada, *T. julis* has established, and parasitism rates range from 14 to 95%[71]. In western Canada, especially in Alberta, the parasitoid is established and controls cereal leaf beetle populations to varying degrees depending on site and year[11]. Parasitization occurs from mid-late May and continues until the end of June. Peak parasitization in June has been the usual trend. Second generation parasitoids parasitize late maturing *O. melanopus* larvae and such parasitoid larvae overwinter inside infested larval cocoons and start the cycle again (Kher, unpublished data) (Fig. 3).

Fig. 3. Phenology of *T. julis* in southern Alberta and Saskatchewan

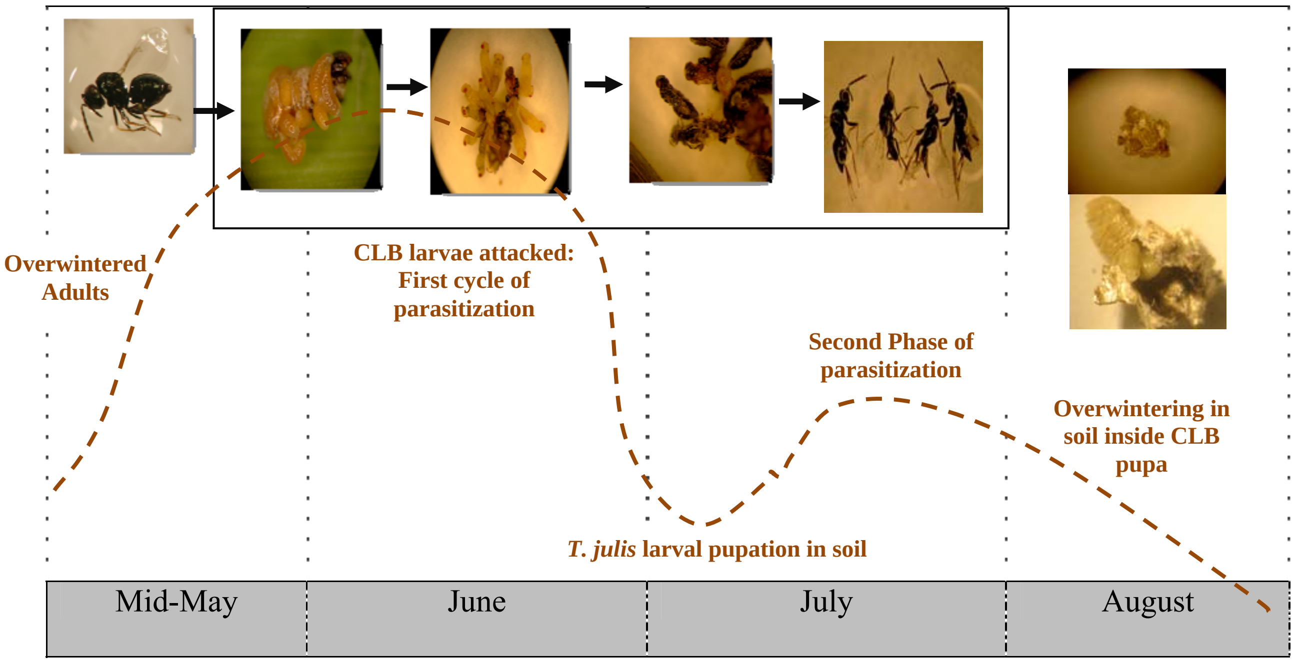

Illustration and Photos of developmental stages of *T. julis*: Swaroop Kher (Source: Kher, unpublished data)
Photo: *Tetrastichus julis* overwintered adult by Dr. L. M. Dosdall

The second major parasitoid of the cereal leaf beetle is the egg parasitoid, *A. flavipes*, which was first discovered from cereal leaf beetle eggs in Pandino, Italy in 1964[75]. It is a minute species measuring less than 1 mm, and was first released in the U.S.A. in 1966[76]. *Anaphes flavipes* has a Europe-wide distribution in countries including Spain, France, Italy, Germany and Yugoslavia[36]. The parasitoid lays varying numbers of eggs in host eggs (with a maximum of eight eggs observed per host egg) which develop in about 10 to 11 days at 21°C[40]. However, the parasitoid is not as successful as *T. julis* in North America due to its asynchrony with peak oviposition activity of the beetle[75]. Other natural enemies of the cereal leaf beetle include the parasitoid of adult beetles. *Hyalomyodes triangulifer* (Loew) (Diptera: Tachinidae), was reported from Michigan[33] and North Dakota[77]. *Trichogramma* sp. is an egg parasitoid in Michigan[78]. *Meigenia mutabilis* (Fallén) (Diptera: Tachinidae) is a larval-pupal parasitoid of the cereal leaf beetle in Russia[79,80]. Sedivy (1995)[81] reported over 10 species of hymenopterous parasitoids in the Czech Republic, including the eulophid species, *Necremnus leucarthros* (Nees), as a gregarious pupal parasitoid. Coccinelid predators like *Hippodamia parenthesis* (Say)*, H. tredecimpunctata* Linneaus and *Coccinella novemnotata* (Herbst) are egg predators, while *Coleomegilla maculata* (De Greer) and *Hippodamia convergens* Guerin prey on eggs and larvae[82,83]. A predatory neuropteran, *Chrysopa* sp., has also been recorded[26]. An egg predator, *Nabis feroides* Remane (Hemiptera: Nabidae) is known from Russia[80]. Pathogens include the fungus, *Alternaria alternata* Keissler[84]. The nematode species, *Steinernema carpocapsae* (Weiser), is also reported as a biocontrol agent of cereal leaf beetle[85].

Research Prospects and Scope for Integrated Pest Management

The current overview of the cereal leaf beetle as a pest in North America underlines the fact that using only a single control strategy cannot guarantee population control, and an integrated pest management system with judicious integration of possible approaches can optimize pest management. In the western Canadian context, the recent invasion by the cereal leaf beetle provides a unique and historically rare opportunity to study and understand the initial dispersal characteristics of the cereal leaf beetle. This is fundamentally important for understanding community assembly dynamics, and initial colonization and dispersal of a pest is the best stage during which to implement management efforts. A systematic approach for research in this case could comprise the following components: 1) routine monitoring and surveillance of pest populations; 2) determining dispersal characteristics over space and time; 3) determining field dynamics with respect to factors such as host plant quality, host plant genotype, and crop canopy characteristics to better understand how and when to intervene with control measures; and 4) integrating different techniques for pest control such as augmentation of indigenous natural enemies, importation and release of *T. julis*, cultural practices, and host plant resistance. In the Canadian context, there is opportunity to explore host plant resistance and the suitability of *T. julis* for the temperate continental climatic conditions that characterize principal areas of cereal production. Natural enemies should prove to have a significant role in controlling pest populations and their augmentation in the field can help ensure timely control of the pest. However, this requires a thorough understanding of the natural enemy complex associated with the pest in a given ecological niche and interrelations with the pest and its host plants. There is a dearth of studies in North America that attempt to explore such interactions and there is an opportunity to study the natural enemy complex of the cereal leaf beetle in its new habitat. Earlier studies have shown that climate change is likely to alter cereal leaf beetle distribution and abundance[15]. However, it remains to be understood how its natural enemies, particularly *T. julis*, would cope with such environmental changes. It is important to understand parasitoid synchronization with beetle dispersal in new areas and in unique landscapes to better predict whether it will be successful in keeping pest populations in check. Finally, effective communication with the farming community on research achievements is crucial for ensuring that appropriate management strategies are implemented.

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