PS&C
Prairie Soils &
Crops Journal



# Integrating the building blocks of agronomy and biocontrol into an IPM strategy for wheat stem sawfly.

Brian L. Beres[1, 2], Héctor A. Cárcamo[2], David K. Weaver[3], Lloyd M. Dosdall[1], Maya L. Evenden[4], Bernard D. Hill[2], Ross H. McKenzie[5], Rong-Cai Yang[1], and Dean M. Spaner[1]
[1]U. of Alberta, Edmonton, Alberta, AB
[2]Agriculture and Agri-Food Canada, Lethbridge, AB
[3]Montana State University, Bozeman, MT
[4]University of Alberta, Edmonton, AB
[5]Alberta Agriculture & Rural Development, Lethbridge, AB
Corresponding authors E-Mail: brian.beres@agr.gc.ca

## Summary

The wheat stem sawfly (*Cephus cinctus* Norton [Hymenoptera: Cephidae]) is a serious threat to wheat (*Triticum aestivum* L.) and other cereal grains in the northern Great Plains. Insecticides have proven ineffective for sawfly control and can be detrimental to beneficial insects. The management of wheat stem sawfly, therefore, requires the integration of host plant resistance, agronomic and biological control strategies. Recent studies in Alberta, Canada have assessed the response of wheat stem sawfly and its natural enemies to cultivar selection, residue management, seeding rates, fertility regimes, and harvest management. Solid-stemmed cultivars are usually agronomically superior to susceptible cultivars when sawflies are present. The stubble disturbance associated with residue management and direct-seeding in a continuous cropping system can reduce sawfly populations compared to a wheat-fallow system. Increased seeding rates can optimize yield, but an inverse, negative relationship between pith expression (stem solidness) and higher seeding rates may occur. Positive yield responses are typically observed with N rates > 30 kg N $ha^{-1}$, but increased insect stem cutting by sawfly can occur with higher N rates. Increasing cutter bar heights during combine harvest can conserve natural enemies, and chopping straw for improved residue management in the spring will not likely affect wheat stem sawfly parasitoids that overwinter in the straw. In summary, an integrated strategy to manage wheat stem sawfly consists of diligent pest surveillance, planting solid-stemmed cultivars, continuous cropping with appropriate pre-seed residue management, seeding rates no greater than 300 seeds $m^{-2}$, 30 to 60 kg N $ha^{-1}$, and harvest cutting heights of at least 15 cm to conserve parasitoids.

## Background and Status

One of the most economically important insect pests of wheat in the northern Great Plains is the wheat stem sawfly (WSS)[1,2,3], (Fig. 1). WSS has been a serious pest of wheat since widespread production of the crop began in the late 19$^{th}$ century[4].

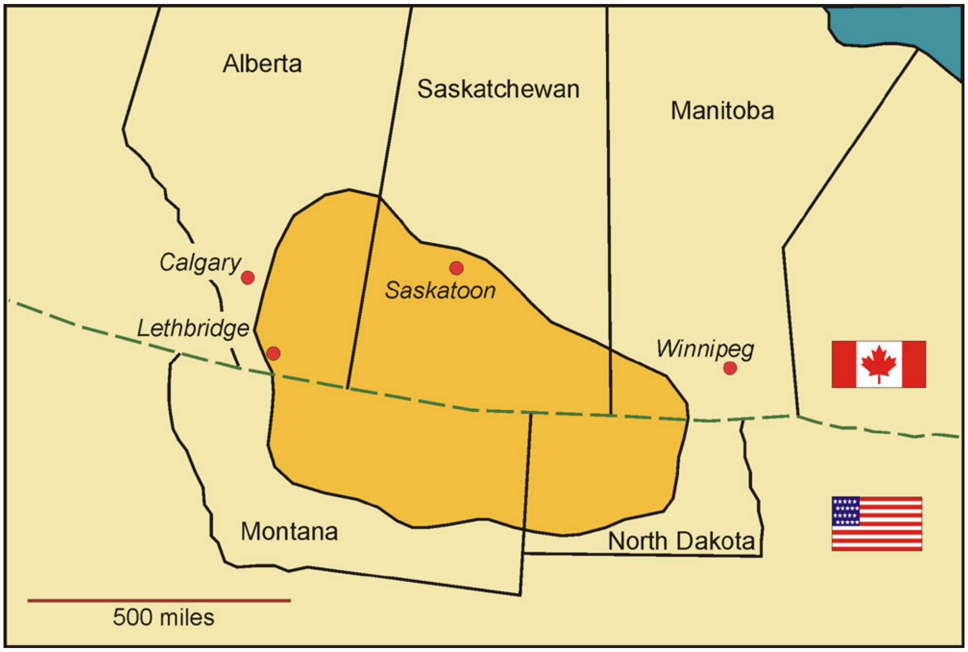


Fig. 1. Area (shaded) historically most affected by wheat stem sawfly.

Adults emerge from the previous year's crop stubble in late spring to early summer and, following mating, the adult female seeks out a suitable host plant to oviposit, usually an adjacent wheat field[5] . A healthy female can successfully lay up to 50 eggs; therefore, the population and subsequent damage to wheat can increase exponentially in a single generation[6]. Shortly after an egg is deposited into a stem of wheat, a larva will hatch and begin boring the stem[7]. This activity continues throughout the growing season until the host plant reaches physiological maturity (Fig. 2a). Chlorosis associated with plant ripening and the reduction of whole plant moisture cues the larva to begin preparation to overwinter[8]. The larva moves to the base of the stem, notches a v-shaped groove around the stem, fills the region with frass, and encases itself in a cocoon below the groove. The groove weakens the stem and causes it to easily lodge or topple over, which proves difficult to recover at harvest[9]. The injury caused by stem boring reduces photosynthetic rates[10] and results in grain weight losses ranging from 10 to 17%[11,12,13]. An additional loss in yield potential occurs when toppled stems are not recovered at harvest[6,1]. Thus, overall yield potential in wheat infested by WSS can be reduced by >25%[2] and the loss of anchored residue leaves fields at risk to soil erosion[14].

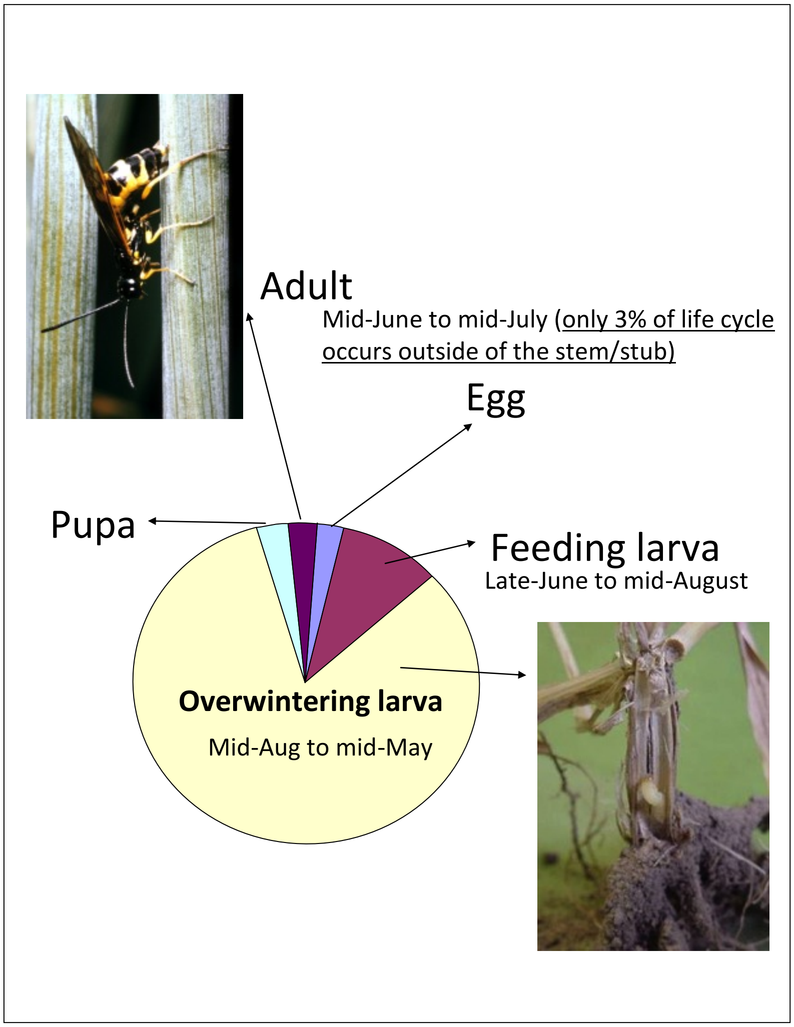


Fig. 2a. Life cycle of the wheat stem sawfly *Cephus cinctus* Norton

There are multiple factors that contributed to a resurgence of the WSS (Fig. 2b). Monoculture wheat production provides the sawfly with an abundance of nearby hosts each spring when the pest emerges from the previous year's infested wheat stubble. Many producers are reluctant to rotate into immune broad leaf crops as continuous wheat provides relatively low economic risk and higher returns compared to other cropping systems in semi arid regions[15]. Continuous or wheat-fallow systems in association with dry weather cycles further enhance WSS populations while wet weather patterns tend to inhibit reproduction and egg deposition[16].
These underlying issues favouring a wheat stem sawfly outbreak are exacerbated in situations where control practices are either absent or used inappropriately. Solid-stemmed cultivars can help to reduce damage caused by stem-boring larvae[1,2,17], can negatively affect female sawflies[18] and cause egg mortality[19]; but these cultivars are only available in the bread wheat class. For example, the entire production area of durum wheat (*Triticum turgidum* L.) in Canada falls within the distribution area for wheat stem sawfly, but no solid-stemmed cultivars are available in this class. Each market class of wheat grown in sawfly-affected areas should have a solid-stemmed option as cultivation of susceptible cultivars perpetuates the cycle that leads to a WSS buildup (Fig. 2b).

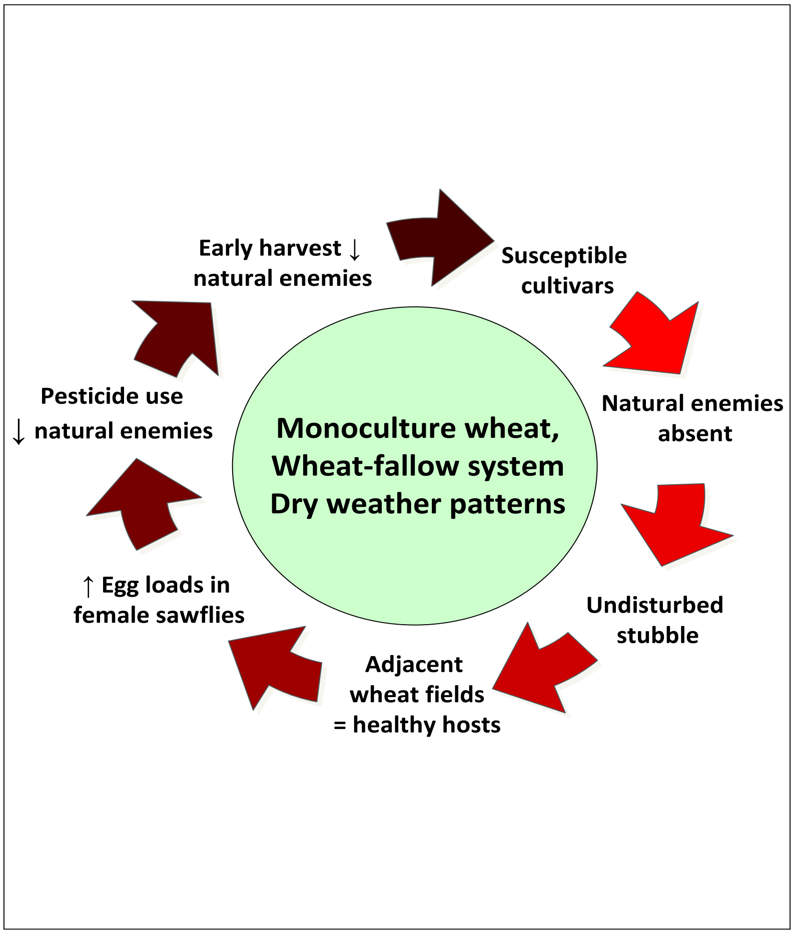


Fig. 2b. Cycle of biological and environmental interactions that facilitated resurgence of the wheat stem sawfly *Cephus cinctus* Norton. Initiated with susceptible cultivars used in monoculture wheat systems, which worsens (represented by darker shades of arrows) when additional factors that favor wheat stem sawfly are present.

Insecticides are generally ineffective management tools to control wheat stem sawfly. Seed-applied insecticides do not provide adequate residual activity to kill larvae, and foliar applications will not completely kill all females before egg deposition. In addition, insecticides will destroy beneficial insect populations[2]. The parasitic wasp *Bracon cephi* (Gahan) (Hymenoptera: Braconidae) is the primary natural enemy of the WSS throughout its range. A closely related species, *B. lissogaster* (Muesebeck), is also quite abundant in a more restricted area centered in the major wheat producing counties of Montana. Both wasps produce two generations per year and overwinter above ground in the second or third internode of the wheat stem[20,21]. Lodged stems of wheat caused by stem cutting of the sawfly require lower cutting heights at harvest, which leads to higher mortality of *B. cephi.* Thus, in addition to continuous wheat or wheat-fallow systems as underlying causes of sawfly resurgence, planting susceptible cultivars and a lack of natural enemies exacerbate sawfly problems (Fig. 2b).

## Assessment of Control Strategies

**Cultivar Development:** All commercially available solid-stemmed spring and winter wheat cultivars developed to date derive resistance from the line S-615, but two other sources exist[2]. The second resistance source is derived from a durum cultivar, Golden Ball, and all studies show that resistance in Golden Ball is more stable and 'solid' across a range of environments than cultivars derived from S-615[17]. The third source is derived from *Agropyron elongatum* L., but attempts to transfer this resistance to common wheat have failed[17]. The recessive nature of the genes controlling resistance derived from S-615 leads to inconsistent pith expression in the field[22]. This was acknowledged shortly after the spring bread wheat cultivar Rescue was released, when observations of high susceptibility to stem cutting were noted at Regina, SK[17]. It was later determined that up-regulation of genes conferring pith development in the culm of a stem is influenced by photoperiod. Intense sunlight results in maximum expression and pith development, whereas shading or cloudy conditions inhibit pith development[23,24]. An attempt to overcome this issue was made by first crossing Golden Ball x *Aegilops squarrosa* L. to create a synthetic hexaploid, then backcrossing the offspring to the hexaploid wheat cultivar, 'AC Elsa'[25,26]. Two germplasm lines were recently released that were developed using this method[27].

Solid-stemmed cultivars currently available in the Canada Red Western Spring class are 'AC Eatonia'[28], 'AC Abbey'[29], and 'AC Lillian'[30]. Solid-stemmed spring wheat cultivars available in Montana include 'Fortuna' and 'Choteau'. Resistance in winter wheat is also important as Montana has a biotype of WSS that has gradually adapted to become synchronous to winter wheat growth phenology by emerging 10 to 20 days earlier than normal. The adaptation seems to have occurred as a response to a shift in acreage away from spring to winter wheat production[31]. Solid-stemmed winter wheat cultivars available to Montana producers include 'Vanguard'[32], 'Rampart' and 'Genou'[33,34].

**Tillage:** In addition to the use of tolerant cultivars, seeding and cultivation strategies used in wheat production can impact insect pest populations[35]. Tillage was one of the first control methods advocated to manage WSS populations. Although considered effective, plowing does not kill all sawflies[6], and it can destroy beneficial insects that attack WSS[36]. The plow was eventually replaced with low disturbance implements such as the Noble blade[37], and concomitant with large blocks of fallow, this change in farming practice likely enhanced WSS populations[38,35]. Other studies investigating tillage as a management tool reported that burial of stubs was not necessary, but removal of soil from the crown was necessary so that overwintering stubs are exposed to lethal temperatures[39]. Similar numbers of larvae emerged from tillage operations that did not remove soil from the crown compared to undisturbed stubble[40]. However, there is disagreement over the efficacy of tillage as a management tool[41], and concern that tillage negatively impacts soil health[42]. A recent study was conducted in southern Alberta to assess effects of implements commonly used in modern conservation farming on sawfly populations. Compared to a wheat-chemical fallow system, the authors report a direct-seeding system that consists of a pre-seed heavy tine harrow operation followed by an air drill equipped with knife openers spaced 30 cm apart reduced WSS adult emergence in spring by 50 – 70% [42].

**Planting Strategies:** Row spacing and seeding rates can influence WSS infestation rates, but this response varies between solid- and hollow-stemmed wheat cultivars. Luginbill and McNeal[43] reported that narrow row spacing and high seeding rates reduced cutting by sawfly in the hollow-stemmed cultivar, Thatcher, but the same treatments reduced pith expression and led to increased cutting levels in the solid-stemmed cultivar, Rescue. Wider row spacing and lower plant densities create more opportunity for light to penetrate the canopy, which leads to greater pith expression[44,45], and a resultant increase in water soluble carbohydrates and drought tolerance[46]. For hollow-stemmed cultivars, high seeding rates and narrow row spacing resulted in lower whole-plant moisture, which is less attractive to ovipositing females than plants with higher moisture content[43].

Seeding date can also influence WSS infestations. An early recommendation was to delay seeding wheat and to plant immune crops such as oats or non-cereals first[5,47]. Jacobsen and Farstad[48] reported that seeding near Lethbridge, Alberta after 21 May reduced high infestation levels to as low as 13%, and also produced significantly more males, which could disrupt mating habits in successive years[49]. Studies in Montana reported that consistently lower infestation levels were only realized with planting dates after 1 June, which seriously erodes the yield potential of the crop[50,51].

Therefore, a realistic approach for "safe" planting dates is to plant fields prone to attack last[51].

**Alternative Planting Strategies:** An early approach to minimize dispersal beyond field edges involved the use of trap crops or border management[2]. An updated approach to trap strips involves within-field border management; i.e., sowing the perimeter of a wheat field to an immune or resistant crop and then planting the interior of the field to a hollow-stemmed wheat cultivar. The goal of this strategy is to intercept incoming sawflies from adjacent infested stubble so that most of the infestation occurs within the trap[52,53]. Blending hollow- and solid-stemmed cultivars may be feasible[2,44]. A Montana study blended hollow- and solid-stemmed cultivars and reported that the strategy was successful for minimizing damage at low to moderate levels of sawfly pressure, but was not feasible if pressure was high[54]. Two Alberta studies reported similar results and noted an 11% increase in yield potential with a 1:1 blend of solid-stemmed 'AC Eatonia' versus the monoculture system of hollow-stemmed cultivar 'AC Barrie'[1,52]. Grain quality was also improved by blending cultivars with contrasting protein accumulation potential[1].

**Nutrient Management:** Crop nutrient management can significantly change crop canopy architecture and influence overall plant health, which in turn could influence WSS infestation rates. Luginbill and McNeal[55] observed that when a blend of nitrogen and phosphorous was applied to wheat there was generally an increase in stem cutting. Nitrogen applied separately did not influence cutting whereas a slight increase in cutting was observed when phosphorous was applied alone. In contrast, a recent Montana greenhouse study reported that phosphorous-deficient wheat plants were most susceptible to sawfly damage[56]. In a Saskatchewan study, no effects of nitrogen or phosphorous could be detected due to the strong influence of environmental factors[57], which is similar to a North Dakota study that reported significantly more sawfly cutting occurred in fertilized plots in only one of eight experiments[58]. The disagreement between these studies underscores the stochastic nature of site-specific, soil-plant fertility dynamics.

## Biological Control

Nine species of Hymenoptera are known to parasitize WSS and are summarized in Meers[59] and Morrill et al.[60]. *Bracon cephi* (Gahan) (Hymenoptera: Braconidae) is the most important parasitoid of WSS in Canada[20] and North Dakota[59]. *Bracon cephi* is bivoltine. The first (overwintered) generation emerges near the time that sawflies appear in mid-May to mid-June. The female wasp immobilizes a host larva with venom and deposits an egg nearby. The larval parasitoid consumes the host larva in about 10 days. The fully developed parasitoid larva spins a cylindrical cocoon and pupates within the stem. New adults emerge in August by chewing circular holes through the stem[20], seek new hosts, and produce another generation that will overwinter as pupae. Successful parasitism by this generation is dependent on crop maturity, which cues the host larva to prepare to overwinter at the base of the wheat plant[61]. If the wheat crop is delayed and crop maturity is not reached until mid-August, the rates of parasitism of the second generation can be very high. If the crop matures early, the host larva usually cuts the stem and is relatively safely housed within its overwintering chamber before the second generation of *B. cephi* has completely emerged[61]. Later seeding would enhance *B. cephi* success, but seeding is now more common in April than May in many parts of southern Alberta. This is partially offset by the adoption of later maturing, high yielding cultivars. Success of *B. cephi* is therefore variable. Mortality of the first generation can be high during harvest because the parasitoid overwinters in the upper internodes of the wheat crop where it is more susceptible to loss from cutting and threshing operations[8]. Low efficacy of *B. cephi* also occurs when activity of the second generation is low.

The second major parasitoid of WSS in wheat is *Bracon lissogaster* (Muesebeck) (Hymenoptera: Braconidae). Like *B. cephi*, *B. lissogaster* was slow to shift to wheat but is now active in Montana and North Dakota[59] and was recently found in southern Alberta (Cárcamo et al., unpublished). The life cycle is similar to *B. cephi* but it can more readily complete a second generation, which is attributed to immediate oviposition of adult females when they emerge[21].

Crop management practices can significantly influence the abundance and efficacy of WSS parasitoids. Reduced tillage resulted in higher rates of parasitism and less stem-cutting than aggressive tillage[36]. Zero tillage cropping systems conserved parasitoids which helped to reduce sawfly populations[35]. Solid-stemmed cultivars also have high levels of parasitism that are comparable to or even higher than hollow-stemmed cultivars[61,62,35]. However, the actual number of parasitoids was not reported in the above published studies. Under high sawfly pressure, there can be a reduction of sawfly cannibalism in solid stems that could lead to multiple larvae in a stem, and would therefore benefit the parasitoid[61]. Conversely, overall numbers of the parasitoid will be lower if the solid-stemmed cultivar drastically reduces the number of available hosts as observed for a synthetic hexaploid line in a recent study near Lethbridge[63]. Blends of susceptible and resistant cultivars may assist to maintain high levels of *B. cephi* over the long term. Conservation of parasitoids can also be accomplished by increasing stubble height at harvest (Meers et al., unpublished) and by avoiding insecticide spraying for grasshoppers along grass ditches where natural enemies of WSS can be abundant.

## A Decision Support Strategy to Manage Wheat Stem Sawfly

Successful management of the wheat stem sawfly requires the distillation of information compiled over the past century into a decision support strategy (Fig. 3). Unlike other serious cereal pests such as orange wheat blossom midge, *Sitodiplosis mosellana* (Géhin) (Diptera: Cecidomyiidae), or the clear-winged grasshopper, *Camnula pellucida* (Scudder) (Orthoptera: Acrididae), insecticidal control has proven ineffective for sawfly control. Therefore, successful management requires a more complex approach[2].

**Pest surveillance and monitoring.** Critically important to the management of wheat stem sawfly are tools that provide an accurate risk assessment of the pest threat (Fig. 3). Large areas of similar cropping ecosystems in the Canadian prairies make the following approach very useful. Risk maps are available and can be reviewed prior to spring sowing[64], which allows producers to make informed decisions regarding cultivar selection, wheat field selection and crop phases. In-crop surveillance is recommended to assess site-specific risk and to determine the need for action based on the level of sawfly infestation (Fig. 3). Predicted risk of cutting damage by wheat stem sawfly can be categorized as low, medium, or high, based on infested stems observed in the ranges of 0-20%, 20-40%, and >40% stems infested, respectively (Fig. 3). A neural network model to predict pith expression in solid-stemmed cultivars has been developed (Beres et al., unpublished; available online at ftp://ftp.agr.gc.ca/pub/outgoing/bb-stb) based on precipitation-related weather data and should be used in conjunction with the risk map. Producers growing a solid-stemmed cultivar can use the model to determine if any action is warranted based on the cutting damage predicted by the model, and the level of threat identified in the risk map. For example, if the neural network model predicts cutting damage in a solid-stemmed cultivar to be >20% in a region where the risk to sawfly is moderate to high, swathing all or a portion of infested fields prior to harvest is recommended so that stems are collected into a windrow before they topple.

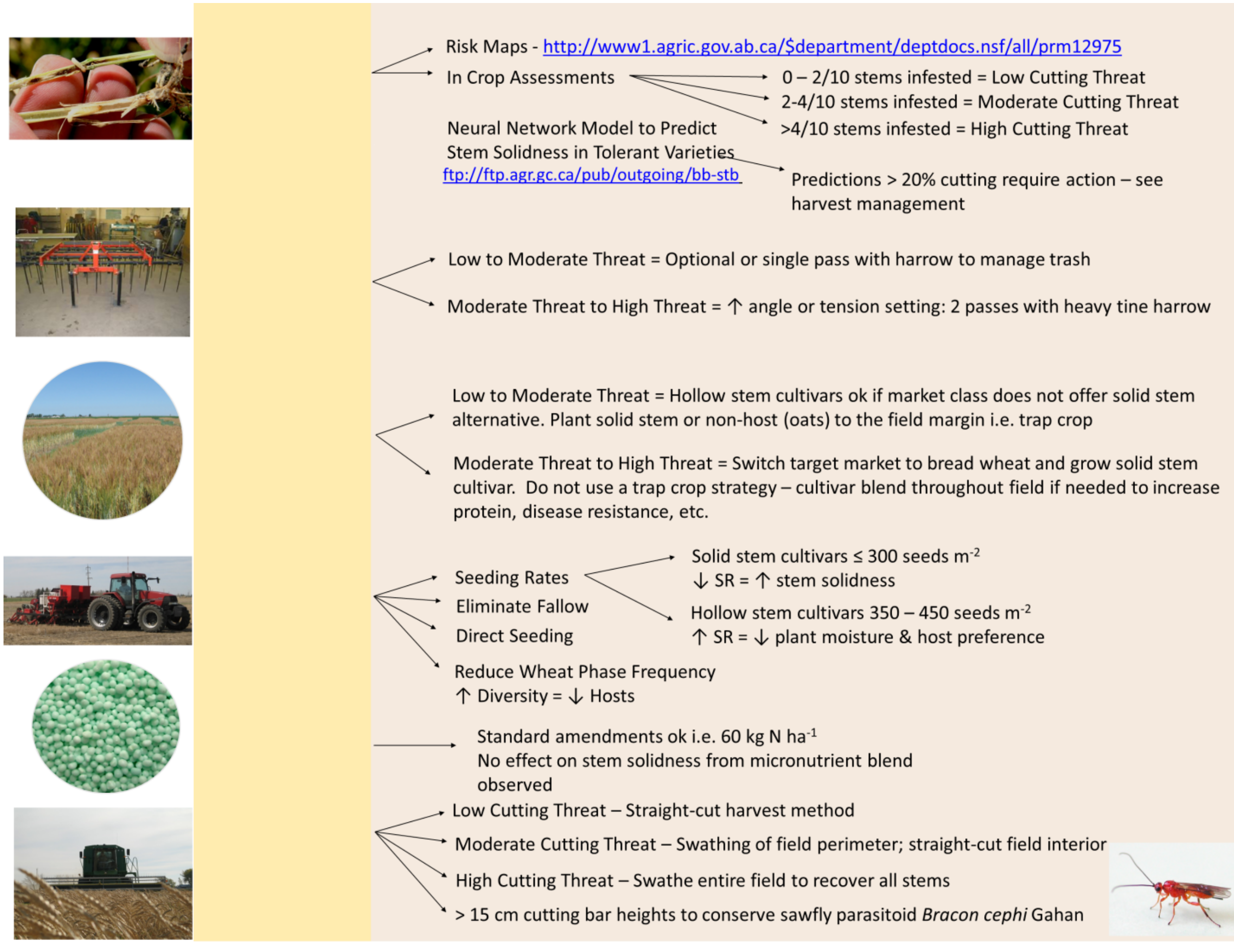


Fig. 3. Decision support schematic for the management of wheat stem sawfly *Cephus cinctus* Norton.

**Crop Management.** A moderate to high threat identified in the risk map would warrant the use of solid-stemmed cultivars or modifications to field selection so that wheat is planted in areas of reduced risk (Fig. 3). Pre-seed harrowing and recropping infested stubble may help to reduce damage in spring wheat and to optimize grain yield[42]. To balance yield potential and pith expression in solid-stemmed wheat, seeding rates should not exceed 300 seeds m$^{-2}$ as canopy shading at higher plant populations inhibits pith expression [44,45]. However, if the producer's business marketing strategy requires cultivars other than bread wheat cultivars, the only class with solid-stemmed cultivars, adjustments to seeding rate is recommended. Hollow-stemmed cultivars should be sown at a density of at least 400 seeds m$^{-2}$ as high yield potential, weed competitiveness, and reduced sawfly damage can be achieved[43] (Fig. 3).

The decision to use an alternative planting strategy should also be based on the predicted sawfly threat (Fig. 3). Trap crops at the field perimeter could be used in low to moderate threat situations because infestation is generally limited to those areas. Therefore, a border of a resistant cultivar or an immune crop such as oats could help reduce sawfly populations (Weaver et al., unpublished). However, the trap strategy may not be effective if the threat is high, as infestations could extend well beyond the field perimeter. The current recommendation is to plant either 1) a non-cereal, 2) a solid-stemmed wheat cultivar, or 3) a blend of solid and hollow stems so that there is a degree of protection throughout the field instead of just along the perimeter (Fig. 3).

Nitrogen management and the use of micronutrient blends will alter canopy architecture in a similar fashion as seeding rates. However, there was no direct effect on pith expression observed in solid-stemmed wheat that was attributed to anything other than shading effects; micronutrient blends did not influence pith expression[45]. Nutrient management should focus on plant health and thus standard amendments are recommended: i.e. 30 – 60 kg N $ha^{-1}$ (Fig. 3).

Harvest management methods should be carefully considered if fields are infested with wheat stem sawfly. The typical harvesting method is to straight-cut standing wheat in a single pass operation using a combine equipped with a straight-cut header and pick up reel. This is acceptable if there is a low cutting threat by WSS. However, if the cutting threat increases to moderate or high, swathing the wheat ahead of the combining operation is necessary to ensure that the stems are gathered into a windrow before they topple. A high threat would require that the entire field be swathed, but swathing of field perimeters may be all that is required if the threat is moderate (Fig. 3).

Harvest management will also significantly affect sawfly parasitoid populations (Meers et al., unpublished). Cutting bar heights >15 cm will help conserve beneficial insect populations. However, this will require an integration of management techniques to minimize cutting by sawfly; low cutting heights are required if too many stems have been toppled over prior to harvest.

In summary, an agronomic strategy to manage wheat stem sawfly consists of diligent pest surveillance, solid-stemmed cultivars, continuous cropping with appropriate pre-seed residue management, seeding rates no greater than 300 seeds $m^{-2}$, 30 to 60 kg N $ha^{-1}$, and harvest cutting heights of at least 15 cm.

## References

1. Beres, B.L., H.A. Cárcamo, and J.R. Byers. 2007. Effect of wheat stem sawfly damage on yield and quality of selected Canadian spring wheat. Journal of Economic Entomology 100:79-87.
2. Beres, B.L., L.M. Dosdall, D.K. Weaver, D.M. Spaner, and H.A. Cárcamo. 2011a. The biology and integrated management of wheat stem sawfly, Cephus cinctus (Hymenoptera: Cephidae), and the need for continuing research. Canadian Entomologist 143:105-125.
3. Weiss, M.J., and W.L. Morrill. 1992. Wheat stem sawfly (Hymenoptera: Cephidae) revisited. American Entomologist 38:241-245.
4. Comstock, J.H. 1889. On a saw-fly borer in wheat. Cornell University, Ithaca, N.Y.
5. Criddle, N. 1922. The western wheat stem sawfly and its control. Dominion of Canada Department of Agriculture Pamphlet No. 6 New Series:1-8.
6. Ainslie, C.N. 1920. The western grass-stem sawfly. U.S.D.A. Technical Bulleting 841.
7. Criddle, N. 1923. The life habits of Cephus cinctus Nort. in Manitoba. Canadian Entomologist 55:1-4.
8. Holmes, N.D. 1979. The wheat stem sawfly. Proceedings of the Twenty-sixth Annual Meeting of the Entomological Society of Alberta. 26:2-13.
9. Ainslie, C.N. 1929. The western grass-stem sawfly: a pest of small grains. . U.S.D.A. Technical Bulletin 157.
10. Macedo, T.B., D.K. Weaver, and R.K.D. Peterson. 2007. Photosynthesis in wheat at the grain filling stage is altered by larval wheat stem sawfly (Hymenoptera : Cephidae) injury and reduced water availability. Journal of Entomological Science 42:228-238.
11. Holmes, N.D. 1977. The effect of the wheat stem sawfly, Cephus cinctus (Hymenoptera: Cephidae), on the yield and quality of wheat. Canadian Entomologist 109:1591-1598.12. Morrill, W.L., J.W. Gabor, E.A. Hockett, and G.D. Kushnak. 1992. Wheat stem sawfly (Hymenoptera: Cephidae) resistance in winter wheat. Journal of Economic Entomology 85:2008-2011.
12. Morrill, W.L., J.W. Gabor, E.A. Hockett, and G.D. Kushnak. 1992. Wheat stem sawfly (Hymenoptera: Cephidae) resistance in winter wheat. Journal of Economic Entomology 85:2008-2011.
13. Seamans, H.L., G.F. Manson, and C.W. Farstad. 1944. The effect of wheat stem sawfly (Cephus cinctus) on the heads and grain of infested stems. Seventy-fifth Annual Report of the Entomolological Society Ontario 75:10-15.
14. Lafond, G.P., S.M. Boyetchko, S.A. Brandt, G.W. Clayton, and M.H. Entz. 1996. Influence of changing tillage practices on crop production. Canadian Journal of Plant Science 76:641-649.

15. Zentner, R.P., C.A. Campbell, F. Selles, P.G. Jefferson, R. Lemke, B.G. McConkey, M.R. Fernandez, C. Hamel, Y. Gan, and A.G. Thomas. 2006. Effect of fallow frequency, flexible rotations, legume green manure, and wheat class on the economics of wheat production in the Brown soil zone. Canadian Journal of Plant Science 86:413-423.17. Platt, A., and C.W. Farstad. 1949. Breeding spring wheats for resistance to wheat stem sawfly attack. Proceedings of the 7th Pacific Science Congress 4:215-220.

16. Wallace, L.E., and F.H. McNeal. 1966. Stem sawflies of economic importance in grain crops in the United States Agricultural Research Service, U.S. Dept. of Agriculture, Washington,

17. Platt, A., and C.W. Farstad. 1949. Breeding spring wheats for resistance to wheat stem sawfly attack. Proceedings of the 7th Pacific Science Congress 4:215-220.

18. Cárcamo, H.A., B.L. Beres, F. Clarke, R.J. Byers, H.H. Mundel, K. May, and R. DePauw. 2005. Influence of plant host quality on fitness and sex ratio of the wheat stem sawfly (Hymenoptera : Cephidae). Environmental Entomology 34:1579-1592.

19. Holmes, N.D., and L.K. Peterson. 1961. Resistance of spring wheats to the wheat stem sawfly, Cephus cinctus Nort. (Hymenoptera: Cephidae) I. Resistance to the egg. Canadian Entomologist 93:250-260.

20. Nelson, W.A., and C.W. Farstad. 1953. Biology of Bracon cephi (Gahan) (Hymenoptera: Braconidae), an important native parasite of the wheat stem sawfly, Cephus cinctus Nort. (Hymenoptera: Cephidae), in Western Canada. Canadian Entomologist 85:103-107.

21. Somsen, H.W., and P. Luginbill. 1956. Bracon Lissogaster Mues., a parasite of the wheat stem sawfly. U. S. D. A. Technical Bulletin 1153:1-7.

22. Hayat, M.A., J.M. Martin, S.P. Lanning, C.F. McGuire, and L.E. Talbert. 1995. Variation for stem solidness and its association with agronomic traits in spring wheat. Canadian Journal of Plant Science 75:775-780.

23. Eckroth, E.G., and F.H. McNeal. 1953. Association of plant characters in spring wheat with resistance to the wheat stem sawfly. Agronomy Journal 45:400-404.

24. Holmes, N.D. 1984. The effect of light on the resistance of hard red spring wheats to the wheat stem sawfly, Cephus cinctus ( Hymenoptera: Cephidae). Canadian Entomologist 116:677-684.

25. Clarke, F.R., T. Aung, and R.M. DePauw. 1998. Simplifying the inheritance of resistance to wheat stem sawfly (Cephus cinctus Nort.). pp. 240-242 Proceedings of the Ninth International Wheat Genetics Symposium, Vol. 3. University Extension Press, University of Saskatchewan, Saskatoon, SK.

26. Clarke, F.R., J.M. Clarke, and R.E. Knox. 2002. Inheritance of stem solidness in eight durum wheat crosses. Canadian Journal of Plant Science 82:661-664.

27. Clarke, F.R., R.M. DePauw, and T. Aung. 2005. Registration of sawfly resistant hexaploid spring wheat germplasm lines derived from durum. Crop Science 45:1665-1666.

28. DePauw, R.M., J.G. McLeod, J.M. Clarke, T.N. McCaig, M.R. Fernandez, and R.E. Knox. 1994. AC Eatonia hard red spring wheat. Canadian Journal of Plant Science 74:821-823.

29. DePauw, R.M., J.M. Clarke, R.E. Knox, M.R. Fernandez, T.N. McCaig, and J.G. McLeod. 2000. AC Abbey hard red spring wheat. Canadian Journal of Plant Science 80:123-127.

30. DePauw, R.M., T.F. Townley-Smith, G. Humphreys, R.E. Knox, F.R. Clarke, and J.M. Clarke. 2005. Lillian hard red spring wheat. Canadian Journal of Plant Science 85:397-401.

31. Morrill, W.L., and G.D. Kushnak. 1996. Wheat stem sawfly (Hymenoptera: Cephidae) adaptation to winter wheat. Environmental Entomology 25:1128-1132.

32. Carlson, G.R., P.L. Bruckner, J.E. Berg, G.D. Kushnak, D.M. Wichman, J.L. Eckhoff, K.A. Tilley, G.F. Stallknecht, R.N. Stougaard, H.F. Bowman, W.L. Morrill, G.A. Taylor, and E.A. Hockett. 1997. Registration of 'Vanguard' wheat. Crop Science 37:291.

33. Bruckner, P.L., G.D. Kushnak, J.E. Berg, D.M. Wichman, G.R. Carlson, G.F. Stallknecht, R.N. Stougaard, J.L. Eckhoff, H.F. Bowman, and W.L. Morrill. 1997. Registration of 'Rampart' wheat. Crop Science 37:1004.

34. Bruckner, P.L., J.E. Berg, G.D. Kushnak, R.N. Stougaard, J.L. Eckhoff, G.R. Carlson, D.M. Wichman, K.D. Kephart, N. Riveland, and D.L. Nash. 2006. Registration of 'Genou' wheat. Crop Science 46:982-983.

35. Weaver, D.K., S.E. Sing, J.B. Runyon, and W.L. Morrill. 2004. Potential impact of cultural practices on wheat stem sawfly (Hymenoptera : Cephidae) and associated parasitoids. Journal of Agricultural and Urban Entomology 21:271-287.

36. Runyon, J.B., W.L. Morrill, D.K. Weaver, and P.R. Miller. 2002. Parasitism of the wheat stem sawfly (Hymenoptera : Cephidae) by Bracon cephi and B-lissogaster (Hymenoptera : Braconidae) in wheat fields bordering tilled and untilled fallow in Montana. Journal of Economic Entomology 95:1130-1134.

37. Mathews, O.R. 1945. Crop residue management in dry-land crop production. Agronomy Journal 37:297-306.

38. McGinnis, A.J. 1950. Sex ratio studies on the wheat stem sawfly, Cephus cinctus Nort. / by Arthur James McGinnis, Montana State College, Bozeman, MT.

39. Holmes, N.D., and C.W. Farstad. 1956. Effects of field exposure on immature stages of the wheat stem sawfly, Cephus cinctus Nort. (Hymenoptera: Cephidae). Canadian Journal of Agricultural Sciences 36:196-202.

40. Goosey, H.B. 1999. In field distributions of the wheat stem sawfly, (Hymenoptera: Cephidae), and evaluation of selected tactics for an integrated management program. Thesis (M S), Montana State University--Bozeman, 1999.

41. Weiss, M.J., W.L. Morrill, and L.L. Reitz. 1987. Influence of planting date and spring tillage on the wheat stem sawfly. Montana Agresearch Montana Agricultural Experiment Station Montana University 4:2-5.

42. Beres, B.L., H.A. Cárcamo, L.M. Dodsdall, M.L. Evenden, R.C. Yang and D.M Spaner. 2011b. Do interactions between residue management and direct seeding affect wheat stem sawfly and grain yield? Agronomy Journal 103:1635-1644.

43. Luginbill, P., and F.H. McNeal. 1958. Influence of seeding density and row spacings on the resistance of spring wheats to the wheat stem sawfly. Journal of Economic Entomology 51:804-808.

44. Beres, B.L., H.A. Cárcamo, R.C. Yang and D.M spanner. 2011c. Integrating spring wheat sowing density with variety selection to manage wheat stem sawfly. Agronomy Journal 103: 1755-1764.

45. Beres, B.L., R.H. McKenzie, H.A. Cárcamo , L.M. Dodsdall, M.L. Evenden, R.C. Yang, D.M. Spaner. 2011d. Influence of seeding rate, nitrogen management and micronutrient blend applications on pith expression in solid stemmed spring wheat. Crop Science. *In Press.*

46. Saint Pierre, C., R. Trethowan, and M. Reynolds. 2010. Stem solidness and its relationship to water-soluble carbohydrates: association with wheat yield under water deficit. Functional Plant Biology 37:166-174.

47. Farstad, C.W., K.M. King, R. Glen, and L.A. Jacobson. 1945. Control of the wheat stem sawfly in the prairie provinces. War-time Production series - Agricultural Supplies Board Special Publication 59:1-7.

48. Jacobson, L.A., and C.W. Farstad. 1952. Effect of time of seeding Apex wheat on infestation and sex ratio of the wheat stem sawfly, Cephus cinctus Nort. (Hymenotpera: Cephidae). Canadian Entomologist 84:90-92.

49. Holmes, N.D., and L.K. Peterson. 1963. Effects of variety and date of seeding spring wheats and location in the field on sex ratio of the wheat stem sawfly, Cephus cinctus Nort. (Hymenoptera: Cephidae). Canadian Journal of Zoology 41:1217-1222.

50. McNeal, F.H., M.A. Berg, and P. Luginbill, Jr. 1955. Wheat stem sawfly damage in four spring wheat varieties as influenced by date of seeding. Agronomy Journal 47:522-525.

51. Morrill, W.L., and G.D. Kushnak. 1999. Planting date influence on the wheat stem sawfly (Hymenoptera : Cephidae) in spring wheat. Journal of Agricultural and Urban Entomology 16:123-128.

52. Beres, B.L., H.A. Cárcamo, and E. Bremer. 2009. Evaluation of alternative planting strategies to reduce wheat stem sawfly (Hymenoptera: Cephidae) damage to spring wheat in the Northern Great Plains. Journal of Economic Entomology 102:2137-2145.

53. Morrill, W.L., D.K. Weaver, and G.D. Johnson. 2001. Trap strip and field border modification for management of the wheat stem sawfly (Hymenoptera : Cephidae). Journal of Entomological Science 36:34-45.

54. Weiss, M.J., N.R. Riveland, L.L. Reitz, and T.C. Olson. 1990. Influence of resistant and susceptible cultivar blends of hard red spring wheat on wheat stem sawfly (Hymenoptera: Cephidae) damage and wheat quality parameters. Journal of Economic Entomology 83:255-259.

55. Luginbill, P., Jr., and F.H. McNeal. 1954. Effect of fertilizers on the resistance of certain winter and spring wheat varieties to the wheat stem sawfly. Agronomy Journal 46:570-573.

56. Delaney, K.J., D.K. Weaver, and R.K.D. Peterson. 2010. Photosynthesis and yield reductions from wheat stem sawfly (Hymenoptera: Cephidae): Interactions with wheat solidness, water stress, and phosphorus deficiency. Journal of Economic Entomology 103:516-524.

57. DePauw, R.M., and D.W.L. Read. 1982. The effect of nitrogen and phosphorus on the expression of stem solidness in Canuck wheat at four locations in southwestern Saskatchewan. Canadian Journal of Plant Science 62:593-598.
58. O'Keeffe, L.E., J.A. Callenbach, and K.L. Lebsock. 1960. Effect of culm solidness on the survival of the wheat stem sawfly. Journal of Economic Entomology 53:244-246.
59. Meers, S.B. 2005. Impact of harvest operations on parasitism of the wheat stem sawfly, Cephus cinctus Norton (Hymenoptera: Cephidae). M.Sc. Thesis, Dept. of Entomology, Montana State University, Bozeman, MT 129 pp.
60. Morrill, W.L., G.D. Kushnak, and J.W. Gabor. 1998. Parasitism of the wheat stem sawfly (Hymenoptera : Cephidae) in Montana. Biological Control 12:159-163.
61. Holmes, N.D., W.A. Nelson, L.K. Peterson, and C.W. Farstad. 1963. Causes of variations in effectiveness of Bracon cephi (Gahan) (Hymenoptera: Braconidae) as a parasite of the wheat stem sawfly. Canadian Entomologist 95:113-126.
62. Morrill, W.L., G.D. Kushnak, P.L. Bruckner, and J.W. Gabor. 1994. Wheat stem sawfly (Hymenoptera: Cephidae) damage, rates of parasitism, and overwinter survival in resistant wheat lines. Journal of Economic Entomology 87:1373-1376.
63. Wu, X.-H., H.A. Cárcamo, B.L. Beres and B.-P. Pang. 2011. Parasitoid *(Bracon cephi)* effects on grain yield of selected genotypes of wheat infested by *Cephus cinctus*. Australian Journal of Crop Science 5:1102-1107.
64. Meers, S.B., and S. Tames. 2010. 2010 wheat stem sawfly forecast [Online]. Available by Government of Alberta http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/prm12975 (posted 21 January 2010; verified 2 December 2010).