Dimethoate insecticide application seldom reduces silvertop incidence in grass seed fields on the Canadian prairies

Authors: Soroka, J.J., and Gossen, B.D.

Source: Canadian Journal of Plant Science, 102(3) : 575-588

Published By: Canadian Science Publishing

URL: https://doi.org/10.1139/CJPS-2021-0187

Canadian Science Publishing

ARTICLE

Dimethoate insecticide application seldom reduces silvertop incidence in grass seed fields on the Canadian prairies

J.J. Soroka and B.D. Gossen

Abstract: Many arthropods have been reported (but none confirmed) as causal agents of sterile seed heads in perennial grass seed fields, known as silvertop or white head. Field studies to identify the arthropods that cause silvertop were conducted in five perennial grass species at seven sites in Saskatchewan, Canada, over several years. The effect timing of insecticide application in spring — early, mid, or late — and of post-harvest residue management — mowing, close mowing with straw removed (scalping), and burning — on subsequent arthropod populations, silvertop incidence, and seed yield were assessed. Samples of grass tillers and sweep net collections were taken regularly, and the arthropods collected were identified to family level and counted. Arthropod populations from sweep samples varied among sites and dates in number and taxon composition, but no arthropod assemblage was consistently associated with silvertop in any grass species. Thrips were the most numerous arthropods on tillers at all sites. Insecticide application often temporarily reduced arthropod populations, but reduced silvertop incidence at only 1 of 15 site-years, and increased seed yield at only 1 of 17 site-years. Scalping or burning did not reduce silvertop incidence but often increased healthy seed head numbers and seed yield relative to mowing, the standard treatment. The majority of Kentucky bluegrass fields had extremely low seed yields unrelated to silvertop or arthropod levels. This extensive study, across a range of grass species and management regimes, provides strong support for the conclusion based on previous work that arthropod pests are not the sole cause of silvertop.

Key words: perennial grass seed production, silvertop, sterile seed heads, insect pests of grasses, insecticide timing, residue management.

Résumé : Maints rapports signalent, sans le confirmer, que les arthropodes sont à l'origine de l'épi argenté, ou coulure des graminées, qui rend l'épi des graminées vivaces stérile. Les auteurs ont entrepris d'identifier sur le terrain, plusieurs années durant, les arthropodes responsables du problème chez cinq espèces de graminées vivaces, à sept endroits de la Saskatchewan (Canada). Ils ont évalué les conséquences du moment où l'insecticide est appliqué (début, milieu ou fin du printemps) et de la méthode de gestion des résidus après la récolte (tonte, scalpage – tonte au ras du sol avec extraction de la paille – ou brûlage) sur la population subséquente d'arthropodes, sur l'incidence de la coulure et sur le rendement grainier. Dans cette optique, ils ont prélevé régulièrement les talles des graminées et recueilli les arthropodes au filet fauchoir afin de les identifier, d'établir la famille à laquelle ils appartenaient et de les dénombrer. Le nombre et le mélange de taxons des arthropodes récoltés au filet varient avec le site, mais aucun groupement d'arthropodes ne présentait de corrélation cohérente avec la coulure, peu importe la graminée. Les thrips sont les plus nombreux sur les talles, à tous les endroits. L'application d'insecticide réduit souvent la population d'arthropodes de façon temporaire, mais n'a diminué l'incidence de la coulure qu'une année-site sur quinze et n'a augmenté le rendement grainier qu'une année-site sur dix-sept. Le scalpage ou le brûlage ne réduisent pas l'incidence de la coulure, mais augmentent fréquemment le nombre d'épis sains et le rendement grainier, comparativement à la tonte, qui est le traitement usuel. La plupart des champs de pâturin des prés ont enregistré un rendement grainier extrêmement faible, sans rapport avec la coulure ni la population d'arthropodes. Cette vaste étude, sur une série de graminées et de techniques agronomiques, appuie fortement la conclusion de travaux antérieurs voulant que les arthropodes parasites ne soient pas les seuls à l'origine de la coulure des graminées. [Traduit par la Rédaction]

Mots-clés : production de graines de graminées vivaces, coulure des graminées, stérilité de l'épi, ravageurs des graminées, application d'insecticide, gestion des résidus.

Received 17 August 2021. Accepted 24 November 2021.

J.J. Soroka and B.D. Gossen. Agriculture and Agri-Food Canada, Saskatoon Research and Development Centre, 107 Science Place, Saskatoon, SK S7N 0X2, Canada.

Corresponding author: B.D. Gossen (email: bruce.gossen@agr.gc.ca).

Introduction

A high incidence of sterile seed heads with a characteristic bleached appearance, a condition known as silvertop, white ear, or white head, can occur in perennial grass seed fields on the Canadian prairies. In grasses such as Kentucky bluegrass (KBG) (*Poa pratensis* L.) and meadow bromegrass (MBG) (*Bromus riparius* Rehm.), the characteristic symptoms of silvertop develop as the spikelet emerges from the boot (Holmes et al. 1961; Soroka and Gossen 2021). Affected seed stalks are pale, eventually becoming silvery white above the last node, and are easily separated from the sheath. Such stalks die without producing viable seed, while other stems and other plant parts remain green and healthy (Soroka 1992; Bailey et al. 2003; Soroka and Gossen 2021). Silvertop occurs in many perennial grass species, but fescues and bluegrasses are especially susceptible (Berkenkamp and Meeres 1975). Cultivars of KBG and other grass species can differ in susceptibility to silvertop (Howard et al. 1996; Loeppky 1999; J.J. Soroka, Agriculture and Agri-Food Canada, unpublished data).

Previous studies have reported over 30 species of arthropods associated with silvertop (Peterson and Vea 1971; Gagné and Gagnon 1984; Bürges et al. 1993). Insects that feed on stems by puncturing sheaths and damaging stems at the base of culms, notably plant bugs in the families Miridae and Capsidae, are most frequently considered to be the principal causes of silvertop (Hardison 1959; Arnott and Bergis 1967; Kamm 1979; Bürges et al. 1993, 1995), while thrips, mites, and leafhoppers also have been associated with this type of injury (Holmes et al. 1961; Kamm 1971; Suski 1984; Chang et al. 1998). The hypothesis that arthropods are the causal agent is supported by studies showing that spring application of insecticide decreased silvertop incidence (Okuda 1988; Chang et al. 1997; Bragg et al. 2002). However, the assumption that the co-occurrence of pest species and silvertop symptoms indicated a causal relationship may be faulty, and could be the reason why the efficacy of control measures is inconsistent.

Fungal pathogens also have been associated with silvertop (Bürges et al. 1993), but other studies indicate that they are not primary causal agents (Hardison 1959; Gagné and Gagnon 1985; Soroka and Gossen 2005, 2021). An attempt to induce silvertop by inoculation with plant bugs and/or pathogens was unsuccessful in both field and greenhouse experiments (Soroka and Gossen 2021). Rather than one species of arthropod causing silvertop, it is possible that pressure from a complex of stressors induces the condition (Soroka and Gossen 2005, 2021).

Residue treatments such as post-harvest burning often reduce silvertop occurrence and severity (Keil 1942; Peterson and Vea 1971; Kamm 1979). This may occur, in part at least, through destruction of overwintering eggs of pests such as plant bugs that have been laid in the grass stems (Hardison 1976). The negative environmental effects of burning have led to assessment of other residue management techniques for silvertop control, and low mowing and removal of clippings after harvest can be as effective as burning for silvertop reduction (Howard et al. 1996; Soroka and Gossen 2005).

The objectives of the current study were to investigate the arthropods associated with seed production in perennial grasses to assess their relation to silvertop injury on the Canadian prairies. The effect of timing of insecticide application and three residue management methods on silvertop incidence and grass seed yields in irrigated and dryland perennial grass seed fields was also evaluated.

Materials and Methods

Research trials were established at seven sites in southern and central Saskatchewan, in areas of relatively low rainfall on the semi-arid Canadian Prairies. Three were commercial grass seed fields, a crested wheatgrass (CWG) (*Agropyron cristatum* (L.) Gaertn.) and a Russian wildrye (RWR) (*Psathyrostachys juncea* (Fisch.) Nevski) field, both near Pambrun, and a KBG field near Birsay; and four were trials at research farms, smooth bromegrass (SBG) *Bromus inermis* Leyss., MBG, and KBG at the Agriculture and Agri-Food Research Farm at Saskatoon, SK, and one site of KBG at the Agriculture and Agri-Food Research Farm at Outlook, SK. Several of the sites were irrigated and others were rain-fed. A summary of the site characteristics is presented in Table 1. The sites were sampled for arthropods approximately weekly from spring to mid-July from 1995 to 1996 or 1997 by sweeping with a standard 37-cm diameter insect net and by collecting and examining grass tillers.

Insecticide treatments consisted of a single application of dimethoate (Cygon® 480 EC insecticide) at two 2-wk intervals (early, mid, late) starting at the end of May, and an unsprayed control. Dimethoate was selected because it had efficacy against a broad spectrum of target grass insects, including aphids, grasshoppers, leafhoppers, mites, several species of plant bugs, stink bugs, and thrips (Ali et al. 1989). Plots were arranged in a randomized complete block design, with four replicates. Dimethoate was applied at 204 g a.i. ha^{-1} and 275 kPa using a hand-held CO_2 pressurized backpack sprayer with a four-nozzle boom, 48-cm spacings between nozzles, and nozzles fitted with 8002 TeeJet flat fan spray tips. Samples of 100 randomly-selected tillers per field were taken weekly from the beginning of May until the first insecticide application; after that, 25 tillers were taken from each treatment weekly or bi-weekly until seed maturity. The growth stage of the tillers was assessed according to the descriptions of Moore et al. (1991), and each tiller was examined using a dissecting microscope for evidence of insect activity. The following factors associated with insect activity were assessed: the

Published by Canadian Science Publishing

Table 1. Grass species and site characteristics of the sites in Saskatchewan that were assessed in the study.

Site characteristics	Pambrun: Crested wheatgrass cv. Kirk	Pambrun: Russian wildrye cv. Swift	Birsay: Kentucky bluegrass cv. Cynthia	Outlook: Kentucky bluegrass cv. Troy	Saskatoon: Smooth bromegrass cv. Carleton	Saskatoon: Meadow bromegrass cv. Regar	Saskatoon: Kentucky bluegrass cv. Dormie
Crop age at start	6 yr	8 yr	3 yr	6 yr	2 yr	2 yr	3 yr
Field size (ha)	81 ha	32 ha	12 ha	< 1 ha	0.5 ha	0.5 ha	0.5 ha
Insecticide trts	1995, 1996	1995, 1996	1995, 1996	1995, 1996	1995–1997	1995–1997	1995–1997
Residue trts	Fall 1995	Fall 1995	1995	Fall 1995, 1996	Fall 1995, 1996	Fall 1995, 1996	Fall 1995, 1996
Irrigation type	none	flood, in 1996 only	Pivot burned fall 1994	wheel run	none	none	Risers
Plot size (m)	30 × 18 m	30 × 18 m	18 × 15 m	4.6 × 37 m	11 × 11 m	11 × 11.5 m	3 × 12 m

Note: Sites were two commercial seed production fields near Pambrun (49°56′6″N, 107°27′28.8″W) and one near Birsay (49°56′6″N, 107°27′28.8″W), and one research site at Outlook (51°30′0″N, 107°3′0″W) and three at Saskatoon (52°8′23″N, 106°41′10″W). trts, treatments.

number of tillers that had insects or insect eggs within them; the number of tillers with insect feeding damage, such as rasping of the epidermis, punctures of the leaf, chewing of the leaf blade, or other feeding damage, or with insect excrement or frass attached to the inside of leaf blades, sheaths, or stems; and the number of tillers that had no evidence of insects.

Further, insect populations were monitored approximately weekly throughout the season by taking five 180° walking sweeps per plot with a standard 38-cm diameter insect net and placing the insects in a plastic bag for later identification. Insects were sorted to Order level, then identified to Family or lower based on morphological characteristics using standard insect keys (Kelton 1980; Triplehorn et al. 2005). Unknown grass feeders associated with high levels of seed head sterility were sent to taxonomists at the Biosystematics Research Division, Agriculture and Agri-Food Canada, Ottawa, ON, for identification. Insect families were categorized as phytophagous or other (which included beneficial or benign organisms); however, because some families such as Miridae included both phytophagous and non-phytophagous species, the comparisons that are presented are for total number of insects and mites collected. In actuality, the majority of insects collected were phytophagous, and in most cases the population curves for total number of insects and for those identified as phytophagous were similar (data not shown).

At late flowering or early seed development, two 25 cm^2 samples of plants were evaluated from each treatment, the numbers of healthy and silvertop heads were counted, and the percentage of heads with silvertop determined as silvertop (%) = (number silvertop stems/number silvertop plus healthy stems) × 100. At harvest, the plants in one or two 25 cm^2 samples from each plot were hand-harvested; entire plots were then harvested with a Hege or Wintersteiger small-plot combine, and seed from both small plots and entire plots were dried, threshed, cleaned, and weighed.

After seed harvest in early autumn of 1995 and 1996, three residue management subplot treatments were applied to each insecticide main plot in a split plot layout, with four replicates. The management treatments were: (*i*) mow — the standing stubble was cut with a rotary mower at about 20 cm height and residue was left on the plots, which is the standard commercial practice; (*ii*) burn — the stubble was ignited with a propane torch and removed by burning; and (*iii*) scalp — the stubble was clipped to 1–2 cm height with a flail mower and the residue raked off.

Seed head counts, silvertop incidence, and seed yield data for each field were analyzed using general linear (PROC GLM) and mixed (PROC MIXED) models for analysis of variance in SAS (SAS 2002). Insecticide and residue management treatments were treated as fixed effects, and years, locations and replicates as random effects. The error term for the insecticide treatments was rep (insecticide), and for residue treatments and insecticide*residue treatment interactions the error term was rep*residue (insecticide). Means were separated using least significant differences with a protected F test at $P \leq 0.05$, unless otherwise stated. Field conditions encountered in the study led to deviations from the experimental protocol (see below). The array of agronomic practices and variations in protocol precluded combined analysis of parameters over sites.

Deviations from standard protocols varied with site and year. For example, the producer did not combine the Pambrun CWG field in 1995 because of poor seed production; the high level of crop residue left in the field forced us to forego the burn treatment at both Pambrun sites (CWG and RWR). Also, the Pambrun RWR field was not irrigated in 1995, but was heavily grazed after combining, with cattle congregating and their excreta accumulating on our plot area. The entire RWR field was aerially sprayed with insecticide on 30 May 1996, and drift may have affected the plot area.

Results

Silvertop data were obtained from insecticide studies for 15 site-years, and the corresponding yield data were obtained for 17 site-years. Data on the effect of residue management on silvertop were obtained from 9 site-years, with yield over 12 site-years. Grasses typically had the first spikelets (R1 growth stage, Moore et al. 1991) emerge from the boot in the first 10 d of June in the majority of site-years, except the KBG plots at Birsay which were slightly later in development in both 1995 and 1996 (Supplementary Tables S1–S16[1]). The burn treatment in KBG at Birsay and Outlook applied in 1995 was associated with severe grass dieback over winter; low numbers of reproductive tillers were found in all three residue treatments at both sites in 1996, as well as in KBG at Saskatoon in 1997. Seed head damage unrelated to silvertop but caused by bromegrass seed midge, *Stenodiplosis bromicola* (Marikovskij and Agafonova), became apparent in SBG and MBG at Saskatoon.

Insects from tillers

Over the course of the 3-yr study, tillers were collected on 104 dates from seven sites, and were analysed from 98 dates (Supplementary Tables 1–16[1]). Although the numbers of arthropods found in tiller samples varied with site and year, taxon composition of arthropods was similar among the five grass species. Thrips, such as the flower thrips *Frankliniella tritici* (Fitch), were the arthropods found in greatest abundance in tillers from all sites in all years. For example in 1996, a year in which tillers were examined from all grasses and spray treatments, 67% of the anthropods found in tillers over the season were grass-feeding thrips, with phytophagous mites placing a distant second at 18%. Leafhoppers, springtails, and miscellaneous flies, beetles, and unknown eggs and egg masses comprised the remainder (Supplementary Table 17[1]). There was no clear pattern of association between insecticide application or residue treatment and the occurrence of arthropod-affected tillers at any site (Supplementary Tables S1–S16[1]).

Insects from sweep samples

The total number of insects collected in five 180° sweeps per sampling date from each of the insecticide treatments at the seven sites over the duration of the study are presented in Figs. 1–5. The arthropod taxon found in the greatest number is indicated below each sampling date in each figure. Most of the phytophagous arthropods collected in sweeps were generalist feeders of graminacaeous plants.

Although arthropods varied in number and species composition with site and year, there was a loose pattern of similar arthropod taxon occurrence among grasses over the growing season. Excluding the bromegrass sites, where bromegrass seed midge became predominant, the greatest numbers of arthropods found in sweeps early in the season in at least 1 yr of sampling were tetranychid mites, principally the clover mite *Bryobia praetiosa* Koch (Figs. 1, 2; Supplementary Figs. S1–S3[1]). The RWR field at Pambrun in 1995 (Fig. 1) had especially heavy foliar damage from mite feeding. Mites were the dominant insect taxon in 6 of the 17 site-years early in the season. They comprised the greatest numbers of arthropods found in 12 of 38 site visits prior to 1 June over all of the years, with seven other taxonomic groups making up the rest (Figs. 1, 2, Supplementary Figs. S1–S3[1]). As the season progressed, thrips and cicadellid leafhoppers became more numerous; by mid-June numbers of mirid plant bugs, especially *Stenodema trispinosa* Reut., increased along with the leafhoppers, and chloropid flies or leafhoppers usually dominated collections at the majority of sites by the end of the sampling period.

The exception to this pattern occurred in the SBG study at Saskatoon (Supplementary Fig. S1[1]), where the oligophagous bromegrass seed midge, *S. bromicola*, was found in low numbers in 1995, and in increasing numbers in 1996 and 1997. The midge was also collected from nearby plots of MBG and KBG, but in much lower numbers than in SBG. Also, high numbers of parasitic Eulophidae wasps were collected from the SBG plot late in the season, thought to be a species of *Aprostocetus* (Westw. 1833) (J. Huber, personal communication, Agriculture and Agri-Food Canada, Ottawa, ON). Eulophidae comprised the insect taxon having highest numbers on SBG on the last sampling dates in all 3 yr, peaking at 344 ± 22 per five sweeps on 2 July 1997. Thrips and leafhoppers comprised the majority of species in MBG plots in all three sampling years.

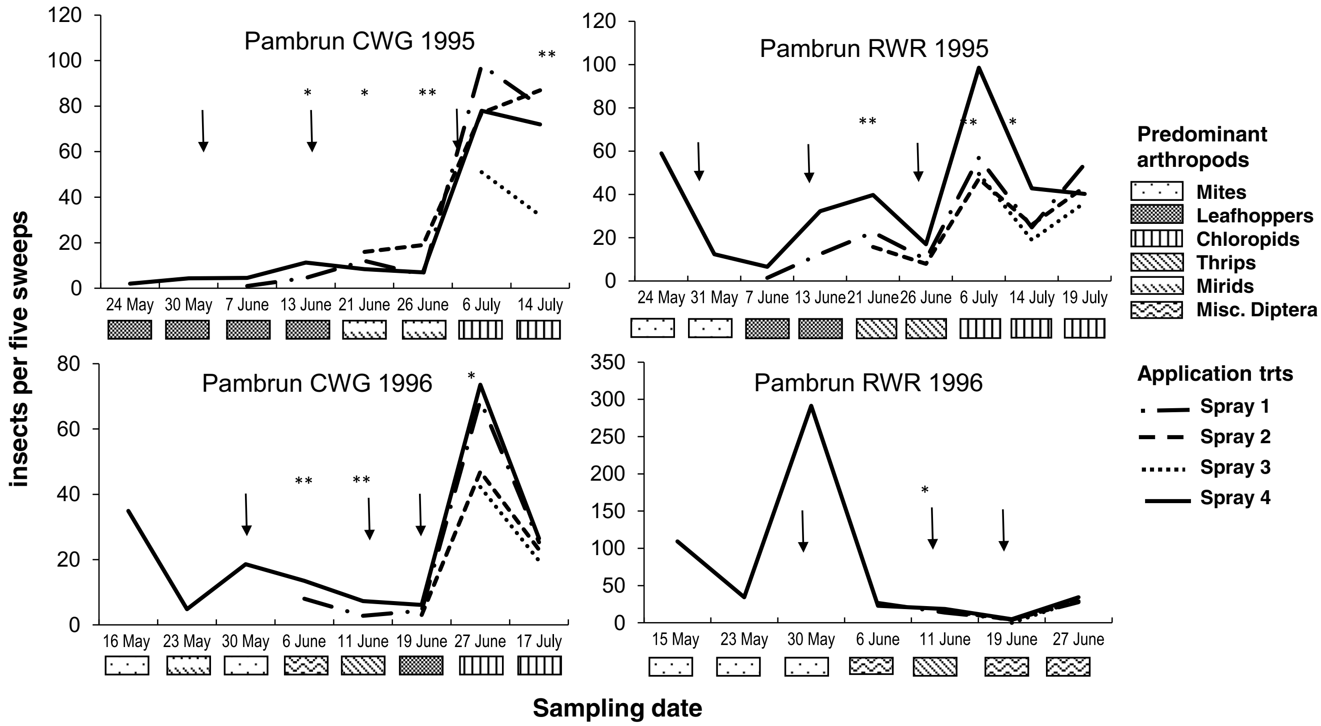
When assessed over the 17 site-years, peak arthropod numbers were higher in KBG fields (Fig. 2, Supplementary Fig. S1[1]) than in other grasses. There were two exceptions to this pattern: high arthropod numbers were found at Pambrun RWR in 1996, which had a peak at 283 ± 48 acarine mites per five sweeps across all treatments on 30 May (Fig. 1), and bromegrass seed midge/Eulophidae wasps in SBG plots at Saskatoon in 1997 (Supplementary. Fig. S2[1]).

Arthropod numbers were usually higher in unsprayed control plots than in insecticide treatments, but significant reductions in arthropod numbers with spray application were found in only 40 of 94 comparisons. Insecticide application typically reduced arthropod numbers in treated plots for 1–2 wk. After that, arthropod levels often rebounded to control levels, especially in plots

[1]Supplementary data are available with the article at https://doi.org/10.1139/cjps-2021-0187.

Published by Canadian Science Publishing

Fig. 1. Effect of early, mid, or late spring applications of insecticide on numbers of arthropods swept from a Kirk crested wheatgrass (CWG) and a Swift Russian wildrye (RWR) field near Pambrun, SK, in 1995 and 1996. Arrows indicate dates of application. Asterisks indicate that the treatments (trts) were significantly different (*, ** = $P \leq 0.05, 0.01$) at that date. The arthropod group collected in greatest numbers from all treatments is indicated by a patterned bar below each sampling date. Misc. Diptera = flies excluding Chloropidae.



sprayed earliest (e.g., CWG at Pambrun in 1995, KBG at Birsay in 1995, and MBG at Saskatoon in 1997).

The appearance and pattern of occurrence of arthropod taxa collected in the residue treatments was similar to those found in the insecticide trials, except that arthropod numbers were less variable among residue treatments (Figs. 3–5) than among spray treatments. Across all grass species, scalp and mow treatments had generally similar numbers of arthropods at each sampling date, and numbers of arthropods in the burn treatment in the bromegrasses were similar to the other residue treatments (Fig. 4). However, arthropod numbers at three of the four KBG sites were lower in the burn treatment than the other residue treatments early in the following season, and the burn treatment at all four KBG sites had fewer total numbers of insects across all sampling dates than the other residue treatments (Figs. 3 and 5).

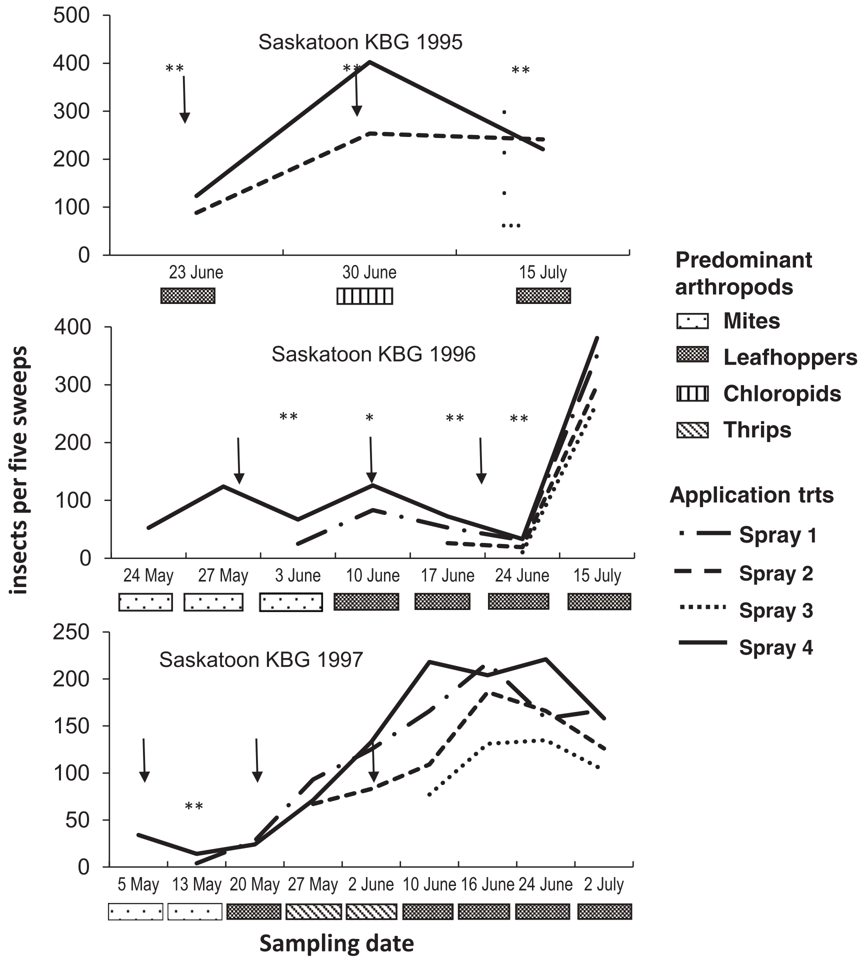
Silvertop levels

Silvertop levels were variable among grass species and years. Silvertop levels were higher than 10% in 4 of 7 KBG site-years (Table 2), but were higher than 10% in only 2 of 8 site-years for the other four grass species (Supplementary Table S18[1]). Silvertop levels over 50% were observed at two sites, Outlook KBG 1995 (Table 2) and Pambrun RWR 1995 (Supplementary Table S18[1]).

There was no consistent association between silvertop parameters and insecticide treatments or arthropod taxa. Insecticide application increased the number of healthy heads relative to the control in only one instance, in KBG at Saskatoon in 1996 ($P = 0.03$) (Table 2). Likewise, there were few differences in number or percentage of seed heads with silvertop among the insecticide treatments. Significant differences were found in number of seed heads with silvertop and silvertop levels among insecticide treatments in CWG at Pambrun in 1995 ($P < 0.05$ for both parameters); unexpectedly, the second spray treatment had a higher number and percentage of seed heads exhibiting silvertop than the other treatments, even though values for the two parameters were low for all treatments (Supplementary Table S18[1]). The second spray treatment had greater numbers of arthropods, predominantly mirid plant bugs, than unsprayed plots on 21 June ($P \leq 0.05$), and greater numbers of arthropods than both the first spray treatment and control plots 5 d later ($P < 0.01$) (Fig. 1), although numbers of arthropods were very low at this site until July.

One site where an association between arthropods and silvertop was found was in RWR at Pambrun, where a high population of the clover mite *B. praetiosa* (Koch) early in the season was associated with high levels of silvertop; peak mite populations averaged 49 ± 19 individuals per five sweeps on 24 May 1995 and 283 ± 48

Fig. 2. Effect of early, mid, or late spring applications of insecticide on numbers of arthropods swept from Dormie Kentucky bluegrass (KBG) plots at Saskatoon, SK, in 1995–1997. Arrows indicate dates of insecticide spray application. Asterisks indicate that the treatments (trts) were significantly different (*,** = $P \leq 0.05$, 0.01) at that date. The arthropod group collected in greatest numbers is indicated by a patterned bar below each sampling date.



individuals per five sweeps on 30 May 1996 (Fig. 1). Extensive mite damage on RWR leaves was present on the first sampling date in 1995, which suggested that mite numbers may have been higher before sampling started. Silvertop levels were much lower in 1996 than in 1995, despite the higher mite numbers in 1996. In both years at this site, the two earliest applications of dimethoate reduced the numbers of seed heads with silvertop and the silvertop percentages below levels in unsprayed plots or those sprayed later, significantly so in 1996 (seed heads $P = 0.01$, silvertop % $P = 0.002$) (Supplementary Table S18[1]). No irrigation was applied to the site in 1995, but the field received ample irrigation throughout the growing season in 1996, which may represent a confounding factor. No other significant differences in silvertop seed heads numbers or levels among spray treatments were found in the study.

Aggressive residue management (burn or scalp) increased the number of healthy seed heads and the number of heads with silvertop, especially in KGB. The Mow treatment had lower numbers of healthy seed heads in 5 of 7 site-years, fewer than either scalp or burn in MBG at Saskatoon in 1997 ($P \leq 0.001$), and in KBG at Saskatoon in 1996 ($P \leq 0.001$) and 1997 ($P = 0.0001$) (Tables 3 and 4), fewer healthy seed heads than scalp in KBG at Outlook in 1996 ($P \leq 0.05$), and fewer than burn in KBG at Outlook in 1997 ($P \leq 0.01$) (Tables 3 and 4). In the 3 site-years with differences among residue treatments in silvertop levels, the mow treatment had fewer heads with silvertop than scalp in all 3 site-years, and fewer than burn in 2 of 3 site-years (MBG 1997 $P \leq 0.05$, Saskatoon KBG 1996 $P \leq 0.01$, Saskatoon KBG 1997 $P \leq 0.01$) (Tables 3 and 4). Silvertop percentage differed among the residue treatments in KGB in 3 site-years, but the pattern of response was not consistent; mow and scalp treatments had higher levels of silvertop than burn at Outlook in 1997 ($P \leq 0.01$), while the mow treatment had lower silvertop levels than burn at Saskatoon in 1996 ($P \leq 0.05$), and lower levels than either burn or scalp at Saskatoon in 1997 ($P \leq 0.01$) (Table 4).

Fig. 3. Effect of three residue management treatments on numbers of arthropods (± standard error) swept from Kirk crested wheatgrass (CWG) and Swift Russian wildrye (RWR) near Pambrun, SK, Cynthia Kentucky bluegrass (KBG) near Birsay, SK, and Troy Kentucky bluegrass at Outlook, SK, in 1996.

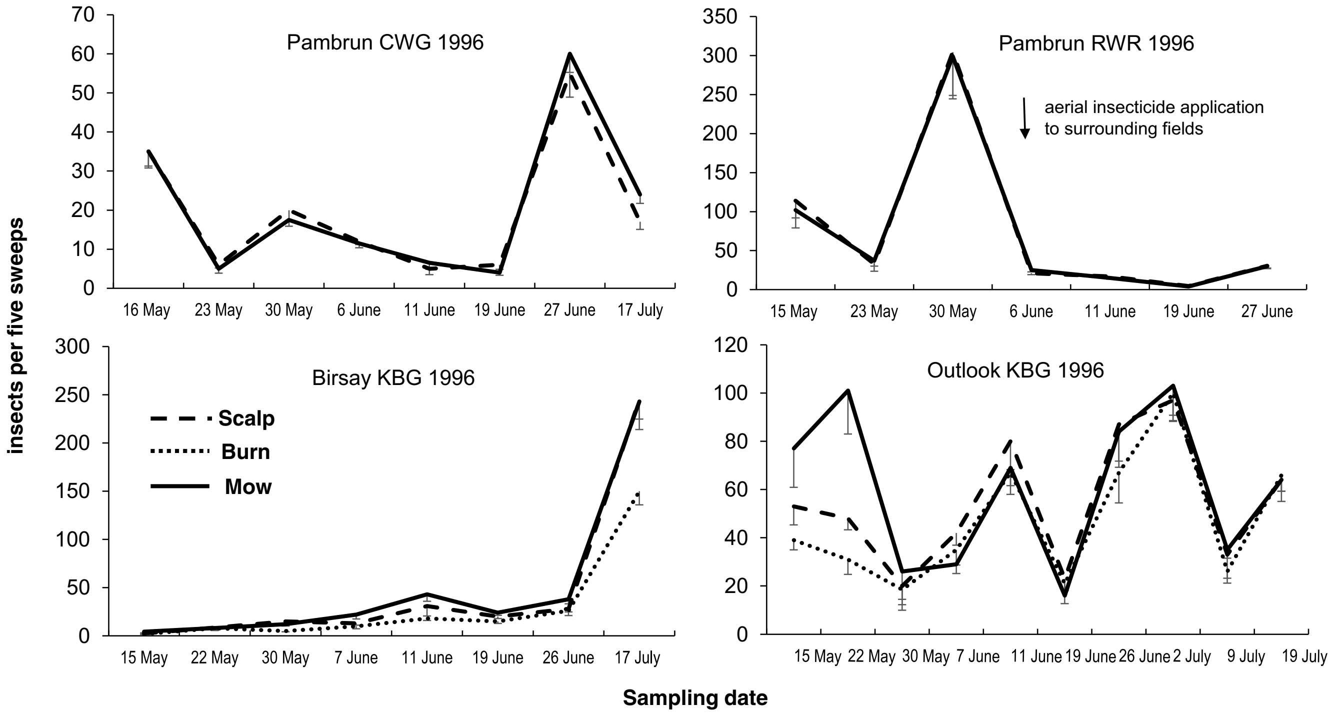


Fig. 4. Effect of three residue management treatments on numbers of arthropods (± standard error) swept from Carleton smooth bromegrass (SBG) and Regar meadow bromegrass (MBG) at Outlook, SK, in 1996 and 1997.

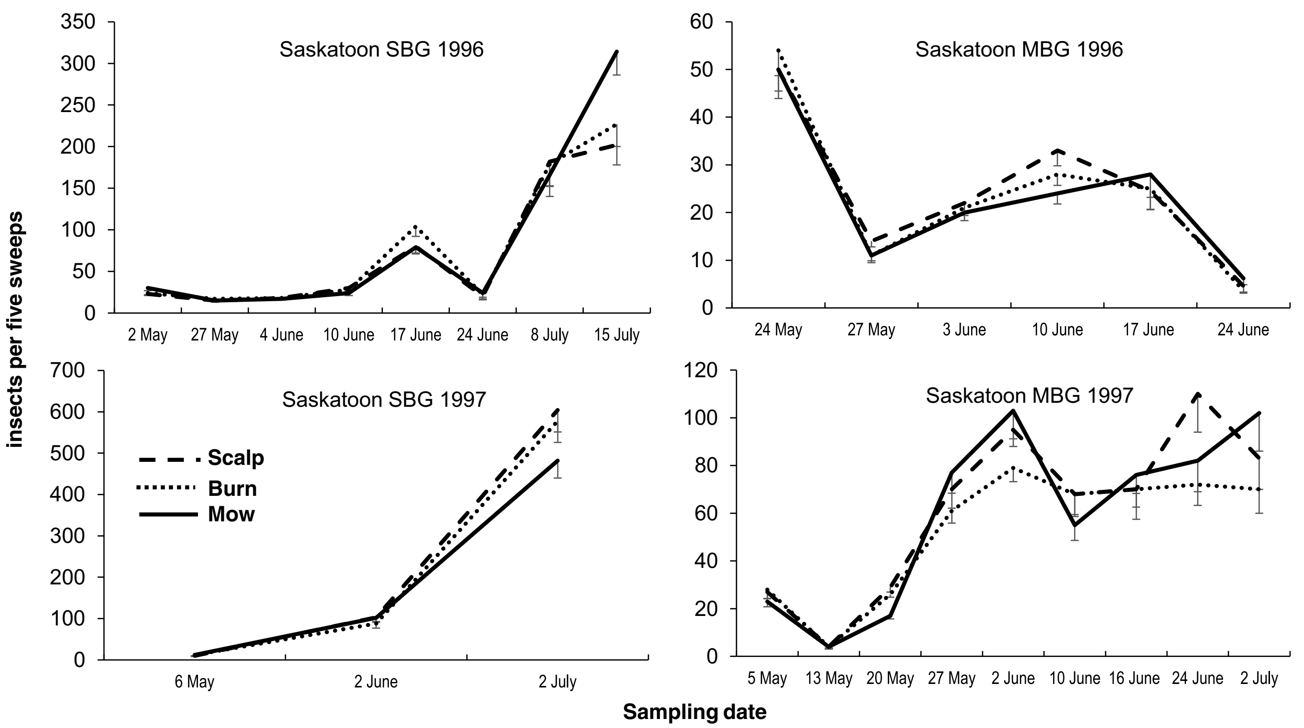
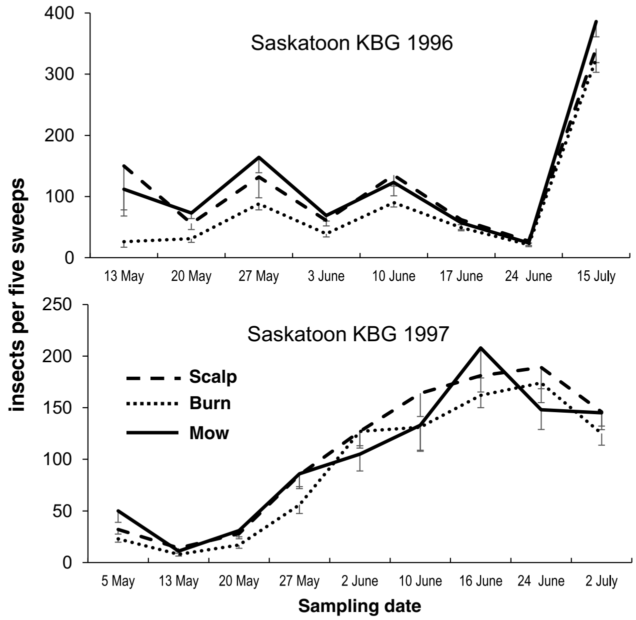


Fig. 5. Effect of three residue management treatments on numbers of arthropods (± standard error) swept from Dormie Kentucky bluegrass (KBG) at Saskatoon, SK, in 1995–1997.



There was only one significant insecticide × residue interaction, for number of silvertop heads of KBG at Saskatoon in 1997 ($F_{6,48} = 2.71$, $P \leq 0.05$) (Table 2). The low frequency of occurrence indicated that this was likely a statistical anomaly, rather than the effect of treatment.

Seed yield

The seed yields in 4 of the 7 KBG site-years evaluated were very low, but yields were fair to good for most of the other grass species compared with normal commercial production. Insecticide treatments had no effect on seed yield in 16 of the 17 site-years (Table 2). The only exception was RWR at Pambrun in 1995, where seed yield for the earliest sprayed treatment was twice or more than that of the other three treatments ($P \leq 0.01$) (Supplementary Table S18[1]). There was a negative relationship between silvertop and seed yield when data from Pambrun RWR were analyzed over both 1995 and 1996, but not in other sites combined over years (data not shown).

Significant differences in seed yield among residue treatments occurred in 7 of 12 site-years. Yield was lower ($P \leq 0.01$) in mow relative to both scalp and burn in 3 site-years (SBG and MBG at Saskatoon in 1997 and KGB at Saskatoon in 1996); lower ($P \leq 0.01$) than only burn in KBG at Saskatoon in 1995 and KBG at Outlook in 1997, and lower ($P \leq 0.01$) than only scalp in CWG at Pambrun in 1996 (Tables 3 and 4). Rain at Birsay in the early fall of 1995 delayed burning, and the heavy KBG regrowth resulted in prolonged plant exposure to a slow moving, hot burn. As a result, subsequent plant stands in the burn treatment were very thin and patchy, and burn seed yield was lower than the other two treatments in 1996 ($P \leq 0.01$) (Table 4). No significant insecticide × residue treatment interaction in yield was found in any site-year.

Discussion

This study was part of a project initiated to develop sustainable production of perennial grass seed production in the semi-arid Prairie region, especially under irrigation, and was conducted in parallel with controlled environment studies of the effect of arthropods on silvertop levels (Soroka and Gossen 2021). The study examined the role of arthropod pests in silvertop expression by monitoring arthropod populations in five species of perennial cool-season grasses over 17 site-years, with and without insecticide application and aggressive residue management treatments. No consistent association was found between arthropod taxon or population size with silvertop incidence, which indicated that arthropods were not the sole or main cause of silvertop. These results provide strong field-based support for the conclusion from a previous study, largely based on controlled environment work, that silvertop is the result of a complex of biotic and abiotic stresses (Soroka and Gossen 2021).

Sampling method strongly affected the amount and types of insects that were collected, but silvertop levels were not consistently associated with arthropod population size or composition at any time period or based on any sampling method. Tiller sampling assessed only those arthropods trapped in the leaf folds of the grasses, and not those arthropods feeding on surface tissues that were vagile, strong fliers or that responded to shadow or

Table 2. Effect of insecticide application on silvertop incidence and seed yield of Kentucky bluegrass (KBG) cvs. Cynthia at Birsay, SK, Troy at Outlook, SK, and Dormie at Saskatoon, SK, 1995–1997.

Date of spray application	Healthy heads (m^{-2})	Heads with silvertop (m^{-2})	Silvertop (%)	Yield ($kg \cdot ha^{-1}$)
Birsay 1995				
30 May	712 ± 123 ns	14 ± 5 ns	2 ± 0.4 ns	314 ± 19 ns
14 June	1066 ± 109	13 ± 9	1 ± 1	386 ± 51
29 June	559 ± 197	8 ± 7	2 ± 1	384 ± 52
Not sprayed	773 ± 212	1 ± 1	0.1 ± 0.1	271 ± 45
1996				
30 May	nd	nd	5 est	20 ± 4 ns
11 June	nd	nd	5 est	34 ± 8
19 June	nd	nd	5 est	23 ± 4
Not sprayed	nd	nd	5 est	23 ± 4
Outlook 1995				
31 May	262 ± 42 ns	320 ± 7 ns	52 ± 4 ns	21 ± 7 ns
13 June	201 ± 52	173 ± 41	45 ± 1	23 ± 4
29 June	279 ± 52	214 ± 42	42 ± 6	23 ± 6
Not sprayed	257 ± 46	195 ± 44	40 ± 9	10 ± 2
1996				
30 May	10 ± 1 ns	1 ± 0.3 ns	14 ± 4 ns	9 ± 1 ns
11 June	12 ± 3	1 ± 0.4	7 ± 2	10 ± 2
19 June	14 ± 3	1 ± 0.3	10 ± 3	9 ± 1
Not sprayed	10 ± 2	1 ± 0.4	7 ± 2	8 ± 2
Saskatoon 1995				
16 June	1952 ± 260 ns	393 ± 51 ns	19 ± 4 ns	138 ± 16 ns
30 June	1772 ± 225	245 ± 51	14 ± 4	151 ± 28
Not sprayed	2129 ± 348	321 ± 82	13 ± 2	135 ± 19
1996				
28 May	1535 ± 129a	100 ± 10 ns	6 ± 1 ns	263 ± 58 ns
10 June	1248 ± 136a	87 ± 13	7 ± 1	220 ± 59
21 June	1332 ± 173a	73 ± 11	6 ± 1	213 ± 45
Not sprayed	825 ± 120b	85 ± 19	8 ± 1	187 ± 22
1997				
05 May	259 ± 32 ns	47 ± 20 ns	12 ± 3 ns	12 ± 2 ns
20 May	188 ± 39	23 ± 4	11 ± 2	8 ± 2
2 June	286 ± 77	33 ± 9	11 ± 3	13 ± 3
Not sprayed	326 ± 57	53 ± 16	11 ± 2	10 ± 2

Note: Values in a column and site-year followed by the same letter do not differ at $P \leq 0.05$ (protected least significant difference). Treatments did not differ from the unsprayed control at $P \leq 0.05$, protected least significant difference, except for the number of healthy heads of Dormie in 1996. est, estimated; nd, no data; ns, not significant; $n = 4$.

movement. One arthropod taxon, Thysanoptera (thrips), predominated in the tiller samples of this study, but there was no strong relationship between evidence of insect presence, numbers, or species of arthropods in tillers and silvertop incidence or seed yield. If thrips were a primary cause of silvertop, silvertop should have been present at relatively high levels at many sites where large thrips populations were present early in the season, but this was not the case.

Many of the arthropods collected by sweeping, including thrips, leafhoppers and plant bugs such as *S. trispinosa*, have previously been associated with silvertop occurrence (Arnott and Bergis 1967; Peterson and Vea 1971; Hardison 1976). However, there was very little association between arthropods and silvertop in the current study, so these results do not support the existence of a causal relationship. Furthermore, most previous reports implicating mites as the initiators of silvertop referred to eriophid mites such as *Siteroptes* spp. feeding in leaf sheaths on the upper part of the stem (Jeppson et al. 2020). High populations of mites in RWR at Pambrun in 1995 occurred in conjunction with high levels of silvertop, but the majority of mites collected in the current study were tetranychids, chiefly *Bryobia* spp. *Bryobia* are cosmopolitan, polyphagous, obligate plant feeders that that prefer to feed on adaxial leaf surfaces early in the growing season (Department of Primary Industries and Regional Development 2015; Anonymous 2018). Foliar feeding by *Bryobea* mites in timothy fields in southwestern Saskatchewan has occasionally been

Table 3. Effect of previous fall residue management treatments on seed yield of Kirk crested wheatgrass (CWG) and Swift Russian wildrye (RWR) near Pambrun, SK, and Carleton smooth bromegrass (SBG) and Regar meadow bromegrass (MBG) at Saskatoon, SK, in 1996 and 1997.

Site, year, and treatment	Healthy heads (m^{-2})	Heads with silvertop (m^{-2})	Silvertop (%)	Yield ($kg{\cdot}ha^{-1}$)
CWG 1996				
Scalp	nd	nd	2 est	272 ± 9a
Mow	nd	nd	2 est	241 ± 11b
RWR 1996				
Scalp	173	9	5 ns	287 ± 39 ns
Mow	218	12	5	316 ± 27
SBG 1996				
Scalp	nd	nd	<1 est	471 ± 34 ns
Burn	nd	nd	<1 est	459 ± 35
Mow	nd	nd	<1 est	456 ± 39
1997				
Scalp	nd	0	0	318 ± 24a
Burn	nd	0	0	340 ± 31a
Mow	nd	0	0	174 ± 14b
MBG 1996				
Scalp	nd	nd	<8 est	267 ± 39 ns
Burn	nd	nd	<8 est	187 ± 31
Mow	nd	nd	9 est	173 ± 19
1997				
Scalp	488 ± 78a	38 ± 8a	9 ± 2ns	141 ± 11a
Burn	368 ± 59a	26 ± 7ab	6 ± 1	173 ± 27a
Mow	69 ± 9b	14 ± 4b	12 ± 3	26 ± 5b

Note: Values in a column and site-year followed by the same letter do not differ at $P \leq 0.05$ (protected least significant difference). est, estimated; nd, no data; ns, not significant; $n = 4$.

severe enough to delay spring regrowth and threaten forage quality (K. Olfert, personal communication, Saskatchewan Agriculture and Food, Swift Current, SK). Also, these mites are foliage feeders and so are unlikely to cause silvertop injury directly to seed heads (E. Lindquist, personal communication, Agriculture & Agri-Food Canada, Ottawa, ON); however, it is possible that the high silvertop levels seen in the RWR field in 1995 were a response of the plant to the combined stresses of heavy phytophagy to leaves and a lack of irrigation during the growing season. The lower silvertop incidence in 1996 relative to 1995, despite much higher numbers of mites but with timely irrigation and less noticeable foliar injury, supports this hypothesis.

There are several possible explanations for the infrequent association between insecticide treatment and silvertop parameters observed in this study. There may have been a lack of synchrony between susceptible growth stages of the grasses and presence of putative arthropod causal agents. However, the highest arthropod numbers occurred well after the grasses reached R1 stage, where grasses might be most susceptible to development of silvertop (Starks and Thurston 1962; Soroka and Gossen 2021), in 10 of the 17 site-years. Mirids, which have been reported to be one of the most common causes of silvertop in western Canada (Arnott and Bergis 1967), were found in considerable numbers on eight occasions in the current study. However, they had little or no impact on silvertop incidence, likely because their greatest numbers occurred later in the season.

Another possibility is that the insecticide was not always effective in reducing arthropod populations. While insecticide application typically reduced arthropod numbers for one or more weeks, in several instances this did not occur. On a few occasions, rain fell shortly after spraying and may have diluted and reduced the efficacy of the insecticide. Dimethoate, which is a broad-spectrum organophosphate, was registered for management of a wide variety of insects and mites in many field crops at the time of this study and is the only insecticide currently recommended for management of multiple insect species in grass seed crops in Saskatchewan (Saskatchewan Ministry of Agriculture 2021). It is unlikely that it was efficacious against all of the phytophagous arthropods in a grass seed crop over the growing season, but there have been no indications over the intervening years that arthropod populations in the region were or have become resistant to this class

Table 4. Effect of previous fall residue management treatments on seed yield of Kentucky bluegrass cultivars Cynthia near Birsay, SK, Troy near Outlook, SK, and Dormie at Saskatoon, SK, in 1996–1997.

Site, year, and residue treatment	Healthy heads (m^{-2})	Heads with silvertop (m^{-2})	Silvertop (%)	Yield ($kg{\cdot}ha^{-1}$)
Birsay 1996				
Scalp	nd	0	0	35 ± 5a
Burn	nd	0	0	8 ± 2b
Mow	nd	0	0	30 ± 3a
Outlook 1996				
Scalp	18 ± 3a	1 ± 1 ns	7 ± 1 ns	9 ± 2 ns
Burn	9 ± 1b	1 ± 1	9 ± 2	8 ± 1
Mow	8 ± 1b	1 ± 1	13 ± 3	10 ± 1
Outlook 1997				
Scalp	39 ± 4b	10 ± 1 ns	20 ± 2a	32 ± 2b
Burn	56 ± 6a	9 ± 1	15 ± 2b	48 ± 2a
Mow	32 ± 2b	10 ± 1	22 ± 3a	30 ± 2b
Saskatoon 1995				
Scalp	2035 ± 280 ns	402 ± 56 ns	20 ± 4 ns	141 ± 14ab
Burn	2138 ± 303	327 ± 82	13 ± 2	159 ± 20a
Mow	1809 ± 186	232 ± 36	12 ± 2	120 ± 18b
Saskatoon 1996				
Scalp	1499 ± 108a	108 ± 12a	7 ± 1ab	233 ± 28a
Burn	1337 ± 140a	104 ± 13a	8 ± 1a	343 ± 52a
Mow	869 ± 108b	47 ± 5b	6 ± 1b	143 ± 18b
Saskatoon 1997				
Scalp	346 ± 54a	41 ± 7b	10 ± 1a	11 ± 2 ns
Burn	330 ± 37a	66 ± 16a	17 ± 2a	13 ± 2
Mow	118 ± 24b	9 ± 2c	7 ± 2b	9 ± 1

Note: Values in a column and site-year followed by the same letter do not differ at $P \leq 0.05$ (protected least significant difference); nd, no data; ns, not significant; $n = 4$.

of insecticides. Finally, non-selective insecticides such as dimethoate can have detrimental effects on biological control agents of phytophagous insects that may outweigh the benefits of the insecticide application on the phytophages. Also, there may have been migration of pests from the untreated field back into the plot area over time. These possibilities may be why the first application treatment, in particular, frequently had arthropod numbers similar to the unsprayed control, especially later in the season.

In this study, few associations were found between insecticide application, silvertop level, and seed yield. Silvertop levels were often below 10%, the nominal threshold of economic injury (Soroka 1992). Occasionally, silvertop was already evident at the time of the first insecticide application, or levels were so high that insecticide treatments had little effect; however, even though insecticide treatment did not always suppress arthropod numbers, it did so often enough that if arthropods were the sole causal agents of silvertop, some evidence of arthropod association with silvertop or seed yield would be expected. Although there was a negative correlation between silvertop and seed yield in RWR at Pambrun, insecticide application had a significant effect on seed head parameters in only 5 of 36 assessments and a significant effect on seed yield in only 1 of 17 site-years. This suggests that the association between insecticide and silvertop/seed yield, and by extension, between arthropod taxa and silvertop or seed yield, is tenuous at best. Likewise, a previous study showed that elevated populations of insects did not consistently affect silvertop levels or seed yields in KBG and MBG in both field and controlled environment trials (Soroka and Gossen 2021). In 1997, other grass trials of various perennial grass species at different ages in central Saskatchewan had low seed yields (Loeppky 1999; Soroka and Gossen 2021). This indicated that a specific factor, likely drought, affected seed yields in that year. Similarly, the extreme low yields of the KBG stands at Birsay and Outlook in 1996 were a result of drastically reduced plant stand because of severe winterkill the previous winter. Winterkill during the winter of 1997 also affected seed set in two cultivars of KBG at Brooks, AB, in 1998 (Chang et al. 1998). A commercial seed producer would likely not invest in an application of insecticide on such weak stands.

Several environmental factors, including late spring frosts, can lead to physiological changes in grasses that cause interruption of nutrient supply to the developing inflorescence and induce silvertop (Malyshev and Henry 2012; Soroka and Gossen 2021). However, we did not receive any reports of unusual late frosts in the course of this study.

In the current study, arthropod species composition was generally similar across grass species and residue treatments. This is consistent with the results of a previous study on KBG, creeping red fescue (*Festuca rubra* subsp. *rubra* L.) and creeping bentgrass (*Agrostis palustris* Huds.) (Soroka and Gossen 2005). Both studies concluded that, where differences in silvertop levels occurred among residue treatments, differences in specific arthropod taxa were not the cause.

Silvertop levels in the residue treatments were generally low in the current study, so it is difficult to draw conclusions regarding the effects of residue treatments on silvertop. However, in the site-years where there were differences in silvertop parameters among residue treatments, mow treatments had fewer healthy seed heads and fewer silvertop heads than scalp and/or burn, and lower levels of silvertop in 2 of 3 site-years. A positive association between numbers of healthy seed heads and those with silvertop also has been reported from MBG subjected to residue treatments (Loeppky 1999). Similarly, increased rates of N fertilizer application increased silvertop rates in several grass species (Pohjakallio et al 1960; Loeppky 1999).

Silvertop was not the principal reason why residue treatments had greater impact than insecticides on seed yields in the current study. Seed yields were influenced much more by the number of healthy heads than by levels of silvertop; the proportional increase in healthy seed heads in scalp and burn over mow treatments was greater than their proportional increase in heads with silvertop, and contributed to higher seed yield. A negative relationship between silvertop levels and seed yields was found in previously mown field plots of KBG and MBG (Soroka and Gossen 2021), but in that study, as in this one, silvertop was not an important determinant of seed yield.

In the current study, the extremely low seed yields in 4 of the 7 KBG site-years provides compelling evidence that factors other than silvertop were driving yield expression. Because of heavy rains in the fall of 1995, all residue treatments were applied very late in the season at Birsay, which may have resulted in very low seed yield the following year (Loeppky and Coulman 2001, 2002; J.J. Soroka, Agriculture and Agri-Food Canada, unpublished data). The seed yield at Outlook may have been affected by the advanced age of the stand, which also may have been the case at Saskatoon KBG in 1997. KBG stands usually remain productive for 3 to 6 yr (Hinman and Schreiber 2001; Margheim et al. 2003; Holman and Thill 2005*b*).

While post-harvest removal of crop residue sanitizes fields by removing insects, weeds, and pathogens (Knowles 1966; Peterson and Vea 1971; Holman and Thill 2005*a*, 2005*b*), a more important aspect of residue management in many grasses comes from removing crop residue, which increases soil surface temperatures and sunlight to the crown. This in turn increases the number of large tillers in the autumn and fertile seed heads the following year (Canode and Law 1979; Chastain et al. 1997; Sylvester and Reynolds 1999; Loeppky and Coulman 2001; Holman and Thill 2005*b*). Differences in response to post-harvest residue management are species- and even cultivar-specific (Young et al. 1998, 1999; Holman et al. 2007). Although some progress has been made in determining the molecular mechanisms controlling perennial grass reproduction, the physiological response of grasses to inductive stimuli is poorly understood (Chastain and Young 1998; Heide 1994; Fjellheim et al. 2014). A better understanding of fall floral induction and winter vernalization requirements for the various grass cultivars grown in western Canada is necessary to fully explain the impact of current-season conditions on grass seed yield. Research also is needed on the cumulative effects of negative biotic and abiotic factors on perennial grass seed yield, and the interaction between grass reproductive development and endogenous stress responses (Soroka and Gossen 2021).

There appears to be a strong genetic component to silvertop expression in some grasses. For example, while SBG usually has silvertop levels that are lower than those found in MBG, hybrids between the two grasses typically have silvertop levels midway between those of their parents (B.D. Gossen, Agriculture and Agri-Food Canada, unpublished data).

Across multiple site years of assessment during the 3 yr of this study, application of dimethoate insecticide had minimal effect on the number of seed heads produced, silvertop levels or seed yield, irrespective of the timing of insecticide application. In contrast, the effect of aggressive residue management the previous fall by burning or close mowing with residue removal varied with grass species, but generally resulted in increased numbers of healthy seed heads and higher seed yield.

Although the research was conducted 25 yr ago, virtually no other work on silvertop has been undertaken on the Canadian prairies since this study was conducted. The breadth of the observations over 17 station-years adds to the limited knowledge base available on silvertop. It supports the conclusions of previous controlled environment and field studies, that specific arthropods by themselves are likely not the principal causal agents of silvertop, but that aggressive residue management can increase seed yield irrespective of silvertop levels (Soroka and Gossen 2005; Soroka and Gossen 2021).

Acknowledgements

We thank Brenda Sorenson, Larry Grenkow, Martin King, Clayton Myhre, Stephanie Harris and our energetic summer students for their technical assistance, T. Williamson, M. Miller, and L. Tollefson for providing research sites, and E.E. Lindquist, K.-W. Wu, and F. Beaulieu, Ottawa Research and Development Centre, Agriculture and Agri-Food Canada, Ottawa, and J. Huber, Canadian Forest Service, Natural Resources Canada, Ottawa, who identified arthropod species. The financial contributions of the Canada-Saskatchewan Partnership Agreement on Water-Based Economic Development, the Canadian Seed Growers' Association, and the Agriculture Development Fund of the province of Saskatchewan for partial funding of the study are gratefully acknowledged.

References

Ali, S., Jones, J.W., Evans, I.R., and Acorn, R.C. 1989. Guide to Crop Protection in Alberta. Part 1. Chemical. AGDEX 606-1. Alberta Agriculture, Edmonton, AB.

Anonymous. 2018. Factsheet *Bryobia praetiosa* Koch 1836. Spider mites of Australia. [Online]. Available from https://keys.lucidcentral.org/keys/v3/spider_mites_australia/key/spider_mites_of_australia/Media/Html/entities/Bryobia_praetiosa_Koch_1836.htm.

Arnott, D.A., and Bergis, I. 1967. Causal agents of silver top and other types of damage to grass seed crops. Can. Entomol. **99**: 660–670. doi:10.4039/Ent99660-6.

Bailey, K.L., Gossen, B.D., Gugel, R.K., and Morrall, R.A.A. (eds.) 2003. Diseases of Field Crops in Canada. Canadian Phytopathological Society. University Extension Press. University of Saskatchewan. Saskatoon, SK. 290 pp.

Berkenkamp, B., and Meeres, J. 1975. Observations on silvertop of grasses in Alberta. Can. Plant Dis. Surv. **55**: 83–84.

Bragg, D.E., Sitton, J., Johnston, W., and Golob, C. 2002. Efficacy of insecticides for control of silvertop disease vectored by grass mealybug in seed fields in 2001. Arthropod Manage. Tests, **27**(1): G11. doi:10.1093/amt/27.1.G11

Bürges, G., Fischl, G., Ivany, K., and Rakk, Z. 1993. Die Weissährigkeit der samengräser und die feldwanzen (Miridae). Med. Fac. Landbouww. Univ. Gent. **58**(2a): 295–297.

Bürges, G., Fischl, G., and Ivany, K. 1995. Investigating the reasons for white-spikedness in Kentucky bluegrass (*Poa pratensis*) grown for seed. J. Appl. Seed Prod. **13**: 39.

Canode, C.L., and Law, A.G. 1979. Thatch and tiller size as influenced by residue management in Kentucky bluegrass seed production. Agron. J. **71**: 289–291. doi:10.2134/agronj1979.00021962007100020017x.

Chang, K.F., Briant, M.A., Howard, R.J., Huggins, S.P., McLean, E.M., and Bandura, L.C. 1997. Efficacy of two insecticides against silvertop on four cultivars of Kentucky bluegrass at Brooks, Alberta, in 1997. 1997 Pest Manage. Res. Rep. #58. Agriculture and Agri-Food Canada, Ottawa, ON. pp. 147–153. [Online]. Available from https://phytopath.ca/wp-content/uploads/2014/09/pmrr_1997.pdf.

Chang, K.F., Briant, M.A., Sims, S.M., Howard, R.J., Motta, J.A., and Pruski, K.W. 1998. Efficacy of two insecticides against silvertop on two cultivars of Kentucky bluegrass at Brooks, Alberta, in 1998. 1998 Pest Manage. Res. Rep. #52. Agriculture and Agri-Food Canada, Ottawa, ON. pp. 146–152. [Online]. Available from https://phytopath.ca/wp-content/uploads/2014/09/pmrr_1998.pdf.

Chastain, T.G., Kiemnec, G.L., Cook, G.H., Garbacik, C.G., Quebbeman, B.M., and Crow, F.J. 1997. Residue management strategies for Kentucky bluegrass seed production. Crop Sci. **37**: 1836–1840. doi:10.2135/cropsci1997.0011183X003700060029x.

Chastain, T., and Young, W. 1998. Vegetative plant development and seed production in cool-season perennial grasses. Seed Sci. Res. **8**: 295–301. doi:10.1017/S0960258500004190.

Department of Primary Industries and Regional Development. 2015. Diagnosing bryobea mite. Government of Western Australia. Department of Primary Industries and Regional Development. Perth, Australia. [Online]. Available from https://www.agric.wa.gov.au/mycrop/diagnosing-bryobia-mite.

Fjellheim, S., Boden, S., and Trevaskis, B. 2014. The role of seasonal flowering responses in adaptation of grasses to temperate climates. Front. Plant Sci. **5**: 431. doi: doi:10.3389/fpls.2014.00431. PMID:25221560.

Gagné, S., and Gagnon, C. 1984. La couloure des graminées: état des connaissences. Phytoprotection, **65**: 45–52.

Gagné, S., and Gagnon, C. 1985. Présence et causes possibles de la couloure des graminées chez la fléole des prés au Québec. Can. Plant Dis. Surv. **65**: 17–21.

Hardison, J.R. 1959. Evidence against *Fusarium poae* and *Siteroptes graminum* as causal agents of silvertop in grasses. Mycologia, **51**: 712–728. doi:10.2307/3755899.

Hardison, J.R. 1976. Fire and flame for plant disease control. Annu. Rev. Phytopath. **14**: 355–379. doi:10.1146/annurev.py.14.090176.002035.

Heide, O.M. 1994. Control of flowering and reproduction in temperate grasses. New Phytol. **128**: 347–362. [Online]. Available from https://www.jstor.org/stable/2558331. doi:10.1111/j.1469-8137.1994.tb04019.x. PMID:33874362.

Hinman, H.R., and Schreiber, A. 2001. The effect of the no-burn ban on the economic viability of producing bluegrass seed in select areas of Washington State. Online publication. [Online]. Available from https://research.libraries.wsu.edu/xmlui/handle/2376/4894.

Holman, J.D., and Thill, D. 2005*a*. Kentucky bluegrass production. U. Idaho Dept. Agric. Life Sci. Bulletin 842. Moscow, Idaho. 11 pp. [Online]. Available from https://www.extension.uidaho.edu/publishing/pdf/BUL/BUL0842.pdf.

Holman, J.D., and Thill, D. 2005*b*. Kentucky bluegrass growth, development, and seed production. U. Idaho Dept. Agric. Life Sci. Bull. 843. Moscow, Idaho. 12 pp. [Online]. Available from https://www.extension.uidaho.edu/publishing/pdf/BUL/BUL0843.pdf.

Holman, J.D., Hunt, C., and Thill, D. 2007. Structural composition, growth stage, and cultivar affects [sic] on Kentucky bluegrass forage yield and nutrient composition. Agron. J. **99**: 195–202. doi:10.2134/agronj2006.0047.

Holmes, N.D., Swailes, G.E., and Hobbs, G.A. 1961. The Eriophyid mite *Aceria tulipae* (K.) (Acarina: Eriophyidae) and silvertop in grasses. Can. Entomol. **93**: 643–647.

Howard, R.J., Chang, K.F., Briant, M.A., Madsen, B.M., and Graham, S.G. 1996. Effects of residue removal and cultivar on the incidence of silvertop in Kentucky bluegrass cultivars at Brooks, Alberta, in 1995-1996. 1996 Pest Manage. Res. Rep. #132. Agriculture and Agri-Food Canada, Ottawa, ON. pp. 259–261. [Online]. Available from https://phytopath.ca/wp-content/uploads/2014/09/pmrr_1998.pdf.

Jeppson, L.R., Keifer, H.H., and Baker, E.W. 2020. The Penthaleidae Oudemans. Mites Injurious to Economic Plants. University of California Press, Berkeley, CA. pp. 318–324.

Kamm, J.A. 1971. Silvertop of bluegrass and bentgrass produced by *Anaphothrips obscurus*. J. Econ Entomol. **64**: 1385–1387. doi:10.1093/jee/64.6.1385.

Kamm, J.A. 1979. Plant bugs: effects of feeding on grass seed development; and cultural control. Environ. Entomol. **8**: 73–76. doi:10.1093/ee/8.1.73.

Keil, H.L. 1942. Control of silvertop of fescue by burning. Plant Dis. Reptr. **26**: 259.

Kelton, L.A. 1980. The plant bugs of the Prairie Provinces of Canada. The Insects and Arachnids of Canada. Part 8. Publication 1708. Research Branch. Agriculture Canada. Ottawa, Canada.

Knowles, R.P 1966. Effect of stubble removal on seed production of bromegrass, *Bromus inermis* Leyss. Agron. J. **58**: 556–557. doi:10.2134/agronj1966.00021962005800050033x.

Loeppky, H. 1999. Flowering and seed production in meadow bromegrass. Ph.D. thesis. University of Saskatchewan. 133 pp.

Loeppky, H.A., and Coulman, B.E. 2001. Residue removal and nitrogen fertilization affects tiller development and flowering in meadow bromegrass. Agron. J. **93**: 891–895. doi:10.2134/agronj2001.934891x.

Loeppky, H.A., and Coulman, B.E. 2002. Crop residue removal and nitrogen fertilization affects seed production in meadow bromegrass. Agron. J. **94**: 450–454. doi:10.2134/agronj2002.4500.

Margheim, J., Baltensperger, D.D., and Cecil, J.T. 2003. Kentucky Bluegrass Seed Production in Western Nebraska and Eastern Wyoming. U. Nebraska EC03-180. Digital Comm. U. Nebraska, Lincoln, NB. [Online]. Available from https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=5759&context=extensionhist.

Malyshev, A.V., and Henry, H.A.L. 2012. Frost damage and winter nitrogen uptake by the grass *Poa pratensis* L.: consequences for vegetative versus reproductive growth. Plant Ecol. **213**: 1739–1747. doi: doi:10.1007/s11258-012-0127-0.

Moore, K.J., Moser, L.E., Vogel, K.P., Waller, S.S., Johnson, B.E., and Pedersen, J.F. 1991. Describing and quantifying growth stages of perennial forage grasses. Agron. J. **83**: 1073–1077. doi:10.2134/agronj1991.00021962008300060027x.

Okuda, M.S. 1988. Evaluation of Decis EC for control of silvertop and *Capsus simulans* in creeping red fescue. Pest. Res. Rep. 1988. Agriculture Canada, Ottawa, ON. p. 134.

Peterson, A.G., and Vea, E.V. 1971. Silvertop of bluegrass in Minnesota. J. Econ. Entomol. **64**: 247–252. doi:10.1093/jee/64.1.247.

Pohjakallio, O., Kleemola, S., and Larhuvaara, L. 1960. On a cause of physiogenic total whiteheads in some grass species. Acta Agric. Scand. **10**: 153–167. doi: 10.1080/00015126009434144.

SAS Institute, Inc. 2002. SAS/Stat software: Version 9.0. SAS Inst., Inc. Cary, NC, USA.

Saskatchewan Ministry of Agriculture. 2021. Dimethoate. P. 679 in Guide to Crop Protection 2021. Saskatchewan Ministry of Agriculture, Regina, Saskatchewan. [Online]. Available from https://www.saskatchewan.ca/business/agriculture-natural-resources-and-industry/agribusiness-farmers-and-ranchers/crops-and-irrigation/crop-guides-and-publications/guide-to-crop-protection.

Soroka, J.J. 1992. Insect pests of legume and grass crops in western Canada. Agriculture Canada Publication 1435/E. Ottawa, ON. 39 pp.

Soroka, J.J., and Gossen, B.D. 2005. Phytophagus arthropods and silvertop levels associated with post-harvest residue treatments in three turfgrass species grown for seed. Can. J. Plant Sci. **85**: 213–224. doi:10.4141/P03-144.

Soroka, J.J., and Gossen, B.D. 2021. Silvertop in perennial grass seed production: Effects of type and timing of biotic stresses. Can. J. Plant Sci. **101**: 621-631. doi:110.1139/cjps-2020-0243.

Starks, K.J., and Thurston, R. 1962. Silvertop of bluegrass. J. Econ. Ent. **55**: 865–867. doi:10.1093/jee/55.6.865.

Suski, Z.W. 1984. On the identity of Pyemotid mites associated with the silver-top disease of grasses. Pages 174–179 in Acarology VI. Vol. 1. D.A. Griffiths and C.E. Brown, eds. Ellis Horwood Ltd.

Sylvester, A.W., and Reynolds, J.O. 1999. Annual and biennial flowering habit of Kentucky bluegrass tillers. Crop Sci. **39**: 500–508. doi:10.2135/cropsci1999.0011183X003900020034x.

Triplehorn, C.A., Johnson, N.F., and Borror, D.J. 2005. An Introduction to the Study of Insects. 7th ed. Thompson Brooks/Cole. Pacific Grove, CA.

Young, W.C., III, Gingrich, G.A., Silberstein, T.B., and Quebbeman, B.M. 1998. Post-harvest residue management of creeping red and Chewings fescue seed crops. Agron. J. **90**: 69–73. doi:10.2134/agronj1998.00021962009000010013x.

Young, W.C., III, Mellbye, M.E., and Silberstein, T.B. 1999. Residue management of perennial ryegrass and tall fescue seed crops. Agron. J. **91**: 671–675. doi:10.2134/agronj1999.914671x.