Temporal and geographical distribution patterns of cabbage seedpod weevil (Coleoptera: Curculionidae) in canola

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Abstract—The cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Marsham), was discovered infesting canola [*Brassica napus* L. and *Brassica rapa* L. (Brassicaceae)] in southern Alberta in 1995, and by 1999 its populations had reached outbreak densities. The weevil has dispersed rapidly through cropland in the southern prairies, prompting this study to assess its potential for establishment in Canada's primary region of canola production in the Moist Mixed Grassland and Aspen Parkland ecoregions. In this study, both short- (24 h) and long-term (4 years) distribution patterns of cabbage seedpod weevil were examined, and these data were combined with previously published ecological findings and meteorological data in CLIMEX™ software to predict regions of western Canada where economically important infestations are likely to occur. Adult temporal distributions over 24 h on canola in bud and flower remained restricted primarily to the inflorescence rather than on stems and leaves regardless of time of day. Surveys conducted in commercial canola fields from 1997 to 2000 recorded rapid dispersal of the species to the north and east from the region of southern Alberta where it was initially found. Dispersal occurred at a rate of approximately 55 km/year, and in 2000 *C. obstrictus* populations were found in Saskatchewan for the first time. The CLIMEX™ model predicts that the distribution of *C. obstrictus* will eventually encompass the entire region of canola production in western Canada.

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Résumé—Le charançon de la graine du chou, *Ceutorhynchus obstrictus* (Marsham), a été découvert dans les cultures de colza [*Brassica napus* L. et *Brassica rapa* L. (Brassicaceae)] du sud de l'Alberta en 1995 et, déjà en 1999, les populations avaient atteint des proportions épidémiques. Le charançon s'est répandu rapidement dans les terres cultivées du sud des Prairies, ce qui a donné le coup d'envoi à cette étude pour évaluer la probabilité de son établissement dans la principale zone de production canadienne de colza, dans les écorégions des prairies humides mixtes et des tremblaies-parcs. Au cours de notre étude, les patterns de répartition à court terme (24 h) et à long terme (4 ans) du charançon de la graine du chou ont été

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examinés et ces données ont été combinées à des données écologiques déjà publiées et à des données météorologiques du logiciel CLIMEX™ pour permettre de prédire quelles régions de l'ouest du Canada sont le plus susceptibles de subir des infestations d'importance économique. Les répartitions temporelles des adultes au cours de périodes de 24 h sur le colza, dans les bourgeons et dans les fleurs, étaient restreintes aux inflorescences et ne s'étendaient ni aux tiges, ni aux feuilles, indépendamment de l'heure de la journée. Des inventaires de champs commerciaux de colza de 1997 à 2000 ont mis en lumière la dispersion rapide de l'espèce de la région sud de l'Alberta, où elle est d'abord apparue, vers le nord et vers l'est. La dispersion s'est faite à raison d'environ 55 km/année, et en 2000, des populations de *C. obstrictus* ont été trouvées pour la première fois en Saskatchewan. Le modèle CLIMEX™ prédit que la répartition de *C. obstrictus* couvrira éventuellement toute la région productrice de colza de l'ouest du Canada.

[Traduit par la Rédaction]

Introduction

The cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Marsham) (Coleoptera: Curculionidae), is a serious pest of cruciferous crops in Europe and North America (Dmoch 1965; McCaffrey 1992; Buntin *et al.* 1995; Cárcamo *et al.* 2001). It is native to Europe (Hoffman 1954; Bonnemaison 1957), and it was first reported in North America in the lower mainland of British Columbia in 1931 (McLeod 1962). From there it is believed to have dispersed south and east, and it now occurs throughout much of the United States (Baker 1936; Hanson *et al.* 1948), and it was recently found in Québec (Brodeur *et al.* 2001). *Ceutorhynchus obstrictus* was discovered infesting canola, *Brassica napus* L. and *Brassica rapa* L. (Brassicaceae), in southern Alberta near Lethbridge in 1995 (Dosdall and Dolinski 2001), and since then it has continued to disperse through cropland in the southern prairies.

The cabbage seedpod weevil is univoltine. Sexually immature adults overwinter in protected areas such as beneath leaf litter in shelterbelts and roadside ditches (Carlson *et al.* 1951; Dmoch 1965). In spring, adults fly from these sites to feed on host plants in the family Brassicaceae (Dmoch 1965). Adults are attracted to canola crops in the bud to early-flowering stages (Dosdall and Dolinski 2001). As soon as petal drop and pistil enlargement occur on canola racemes, females can excavate a cavity in an immature pod with their mouthparts and may deposit a white, cylindrical egg into the puncture. The female brushes her abdomen along the pod to disperse an oviposition deterring pheromone (Kozlowski *et al.* 1983; Mudd *et al.* 1997). Eggs hatch in approximately 1 week. Larvae feed on developing seeds within the siliques, and each larva consumes about five seeds (Dmoch 1965). Mature larvae chew small, circular exit holes in the walls of the seedpods, drop to the soil surface, burrow in, and pupate. Adults emerge approximately 10 d later, feed on canola or other cruciferous plants until late in the season when temperatures decline, and remain in diapause throughout winter (Bonnemaison 1957; Dmoch 1965; Ni *et al.* 1990).

Ceutorhynchus obstrictus can cause severe economic losses in canola at several stages in crop development; consequently the species poses a grave threat to Canada's canola industry. When overwintered adults invade crops, primarily in the bud to early-flowering stages, they feed on flower buds causing destruction ("bud-blasting") (Dosdall *et al.* 2001). Plants with severe bud-blasting produce racemes with few pods and may fail to flower when weevil densities are high. Feeding by larvae within seedpods causes seed losses of approximately 18–20% (Dosdall and Dolinski 2001). If environmental conditions are humid after larvae bore exit holes, the pods can be invaded by fungal spores that germinate and destroy additional seeds within the pods.

When new generation adults emerge late in the season, they feed upon seeds within green pods to build up fat stores for overwintering (Dosdall *et al.* 2001).

Within the Prairie ecozone, the range of *C. obstrictus* is still restricted primarily to the Mixed Grassland ecoregion where comparatively little of Canada's canola is produced (Olfert and Chapco 2001); however, there is concern that *C. obstrictus* may spread to the Moist Mixed Grassland and Aspen Parkland ecoregions of western Canada where up to 5 million ha of canola are grown annually.

CLIMEX™ is a dynamic simulation model that allows researchers to estimate the potential distribution and abundance of animal and plant populations (Sutherst and Maywald 1985). Of particular interest to insect pest managers, the software has been used in a wide range of situations to predict the survival of immigrant insect pests in new environments (Sutherst 1991). The software utilizes the known species distribution and abundance as well as meteorological data to produce a species-specific predictive model based on parameters that affect biological systems. The model derives Ecoclimatic Index (EI) values that describe the suitability of specific locations for species survival and reproduction. The EI values are obtained by combining a Growth Index (GI) with stress indices (dry, wet, cold, and hot) which describe the probability that a population will survive through any unfavorable season (Maywald and Sutherst 1987). The parameters include temperature, light, moisture, heat stress, cold stress, and moisture stress. The model can be used to predict the geographic range for regions where the species does not currently occur.

The objectives of this study were to document changes in the temporal and geographical distributions of *C. obstrictus* in western Canada, over short (24 h) and longer (4 years) time lines, and to predict the potential for range expansion of cabbage seedpod weevil throughout western Canada using CLIMEX™.

Materials and methods

Short-term (24 h) distributions on plant parts

Weevil distributions were observed over 24-h periods on individual host plants in the bud and flowering stages in canola fields near Lethbridge, Alberta (49°27′N, 112°39′W). In 1999, 25 plants of *B. napus* in bud (Growth Stage 3.1 of Harper and Berkenkamp 1975), with at least one adult *C. obstrictus* per plant, were marked with flags and observations were made every 2 h to determine numbers of weevils positioned on the buds, leaves, and stems of each plant. The observation period extended over 24 h from 18 to 19 June. In 2001, hourly observations were made on 25 plants of *B. napus* in full flower (Growth Stage 4.2 of Harper and Berkenkamp 1975) to determine the numbers of weevils positioned on the inflorescence, leaves, and stems. Plants each had at least one weevil per plant at the outset of the observation period, which extended over 24 h from 3 to 4 July. Observation periods in 1999 and 2001 occurred when winds were calm and skies were clear (<25% cloud cover).

To determine whether statistically significant differences occurred in mean numbers of weevils per plant on the inflorescence *versus* stems *versus* leaves over each entire 24-h observation period, data were transformed logarithmically [log(x + 1)] to stabilize variances and subjected to analysis of variance (ANOVA) and Tukey's Studentized range test (SAS Institute Inc 1990).

Long-term (1997–2000) distributions

From 25 June to 10 July, when most canola crops in southern and central Alberta and Saskatchewan were in full flower (Growth Stages 4.2–4.3 of Harper and

Berkenkamp 1975), 105, 123, 105, and 227 canola fields were sampled in 1997, 1998, 1999, and 2000, respectively. A single sample was collected from each field consisting of twenty-five 180° sweeps with a standard insect sweep net. Sampling commenced at the field edge and progressed inward over a distance of about 25–30 m. The geographical location of each field was determined using high resolution maps or hand-held global positioning system units (MagellanTrailblazer XL® Personal Satellite Navigation System). Entire sweep net contents were either stored in plastic bags and frozen or were preserved in jars containing 70% ethanol until sorted, and *C. obstrictus* specimens counted and recorded.

In 1997, fields were sampled in Alberta only, in an area extending from Red Deer (52°11′N, 113°54′W) south to the United States border, east to the Saskatchewan border, and west to the limits of canola production in the foothills of the Rocky Mountains. From 1998 to 2000, sampling included this region of central Alberta, in addition to fields in western Saskatchewan, in an area extending south from North Battleford (52°46′N, 108°15′W) to the United States border and east to Swift Current (50°17′N, 107°41′W).

The numbers of *C. obstrictus* adults collected at each site were used to generate surface maps of cabbage seedpod weevil abundance with "potential mapping" in SPANS GIS™ version 5.31 for OS/2 (PCI Geomatics, Richmond Hill, Ontario), a geographic information systems (GIS) software. This procedure calculates a value for square cells, which form the map as a weighted average of the values of the point data from the survey. A classification scheme was used to group cells according to the calculated weighted averages.

Climate model development

Meterological data for the period 1997 (when *C. obstrictus* was first discovered in Alberta) to 2000 were analyzed to determine whether selected environmental parameters during this time of cabbage seedpod weevil range expansion varied from long-term normal values. Meteorological data for maximum and minimum air temperatures, rainfall, and relative humidity were added to the CLIMEX™ weather station database. The dataset comprised meteorological data for 193 sites across Alberta, Saskatchewan, and Manitoba. The data, from Environment Canada, were based on monthly long-term normal values for the period from 1961 to 1990. A preliminary analysis of meteorological data for Lethbridge, Medicine Hat (50°01′N, 110°43′W), Red Deer, and Peace River (56°14′N, 117°17′W) was conducted to assess air temperature variations among these four Alberta locations. The locations were selected to represent areas of high infestations (Lethbridge and Medicine Hat), low infestations (Red Deer), and areas where cabbage seedpod weevil had not been collected (Peace River).

Initial input parameters for the model were based on previously published ecological studies of *C. obstrictus* and Alberta adult survey data (1997–2000). The model addressed three phases of weevil ecology: overwintering, migration (to and from overwintering sites), and reproduction/development. The primary factor to consider in overwintering is diapause. Ni *et al.* (1990) reported that cabbage seedpod weevil has an obligatory diapause and requires a chilling period of at least 16 weeks at 5°C to break diapause. The timing of weevil migration to and from overwintering sites will influence their pest status in spring-seeded crops such as canola. Dmoch (1965) reported that weevils leave overwintering sites when air temperatures reach 9–11°C; short flights occur at 12°C and longer flights occur at 15°C. Kjær-Pedersen (1992) observed that flight activity increased with warmer temperatures and that maximum flight occurred at 22°C. At the end of the growing season, weevil flights from cropland to overwintering sites cease when air temperatures drop below 15°C (HA Cárcamo, unpublished data). During

TABLE 1. Parameter indices and their values used in the CLIMEX™ model to predict the eventual distribution of *Ceutorhynchus obstrictus* in western Canada.

CLIMEX™ parameter	Index	Value
Temperature	DV0: limiting low average weekly temperature	5
	DV1: lower optimum average weekly minimum temperature	6
	DV2: upper optimal average weekly maximum temperature	25
	DV3: limiting high average weekly maximum temperature	35
Moisture	SM0: limiting low soil moisture	0.000
	SM1: limiting optimal soil moisture	0.100
	SM2: upper optimal moisture	0.275
	SM3: limiting high soil moisture	0.500
Diapause	DPD0: diapause induction day length	14
	DPT0: diapause induction temperature	5
	DPT1: diapause termination temperature (mean weekly minimum)	2
	DPD: diapause development days (days below DPT0 that terminate diapause)	120
	DPSW: summer or winter diapause	0
Heat stress	TTHS: heat stress threshold based on mean weekly maximum temperature	35.00
	THHS: rate of heat stress accumulation	0.02
Dry stress	SMDS: dry stress threshold based on mean weekly soil moisture	0.05
	HDS: rate of dry stress accumulation	0.01
Wet stress	SMWS: wet stress threshold based on mean weekly soil moisture	0.500
	HWS: rate of wet stress accumulation	0.035

NOTE: Indices are required inputs for the CLIMEX™ model, and their values were derived from previously published ecological studies and iteration based on the 1997–2000 survey data.

summer, factors that influence oviposition, hatch, and larval development were important model parameters. Ni *et al.* (1990) found that oogenesis can occur at 9°C, but that 22°C is optimal. Dmoch (1965) reported that egg development requires 5–8 d at 22°C and estimated the time requirements for larval and pupal development from other field studies in Poland. With one exception, mean daily air temperatures were used in the analyses of the parameters in the weevil model. Because maximum temperatures are critical to weevil flight activity, maximum air temperatures, not mean temperatures, were used to identify the time periods early and late in the season when conditions were suitable for migration.

Parameter values were modified individually by an iterative process to develop a best-fit map within CLIMEX™ that approximated distribution and abundance values which occurred in southern Alberta from 1997 to 2000 (Table 1). This process resulted in selection of parameter values that the model used to calculate subsequent EI values (Sutherst *et al.* 1988). EI values range from 0 (not favorable) to 100 (ideal conditions, achievable only under artificially controlled environments); the higher the EI value, the more suitable the location for species survival. Geographic locations where EI values are greater than or equal to 30 represent extremely favorable climatic conditions, conducive for potential pest infestations. Locations with EI values between 20 and 29 are considered favorable for establishment and survival; sites with indices between 10 and 19 are considered marginal; and locations with EI values less than 10 are unfavorable for establishment and survival of the species (Sutherst *et al.* 1988).

The EI values generated by the model were used to develop a surface map of the potential distribution and abundance of *C. obstrictus* in Alberta, Saskatchewan, and Manitoba with SPANS GIS™.

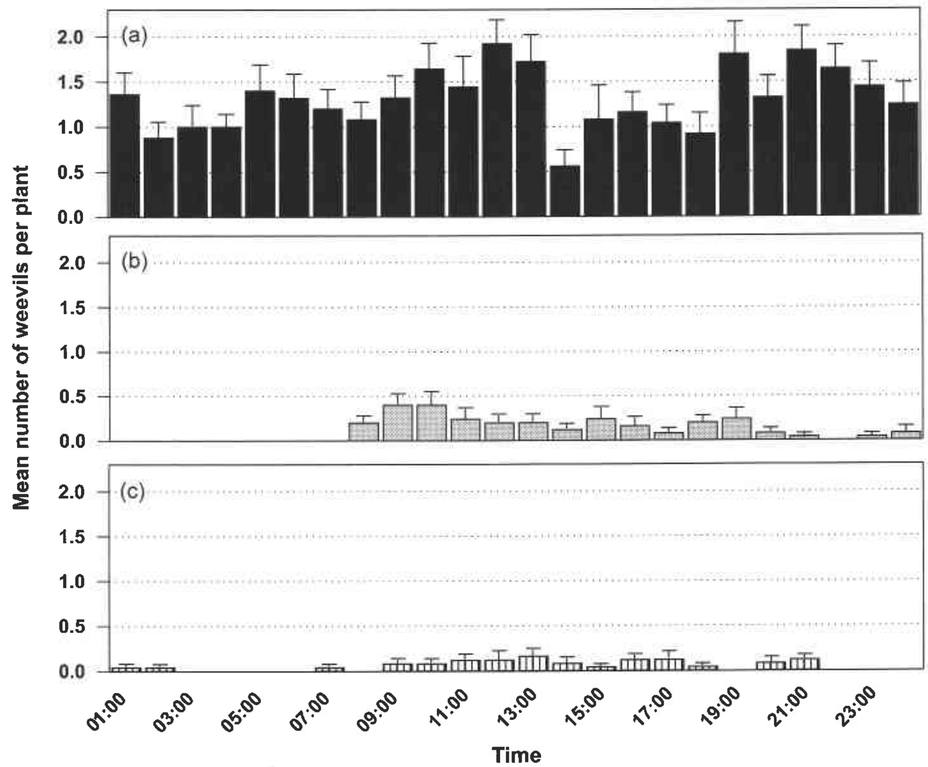

FIGURE 1. Mean + 1 SE numbers of *Ceutorhynchus obstrictus* adults per plant of *Brassica napus* on flowers (*a*), stems (*b*), and leaves (*c*) at different times of day from 3 to 4 July 2001.

Results

Short-term (24 h) distributions on plant parts

Regardless of time of day, *C. obstrictus* adults occurred predominantly on the inflorescence, whether buds (1999 data) or flowers (2001 data). Only results from the 2001 study are presented graphically (Fig. 1), but for canola in both bud and flowering stages, population densities on each plant part were relatively uniform throughout the observation periods, with approximately 3–10 times as many individuals found on buds or flowers *versus* stems or leaves. Averaged over 24 h in 1999, adult weevils per plant on buds (mean ± SE = 3.12 ± 0.08) exceeded those on stems (0.32 ± 0.04) and leaves (0.14 ± 0.02) ($F_{2,897}$ = 613.8, $P < 0.01$). Similarly, over 24 h in 2001 adult weevils on flowers (mean ± SE = 1.31 ± 0.05) exceeded those on stems (0.12 ± 0.02) and leaves (0.05 ± 0.01) ($F_{2,1797}$ = 452.7, $P < 0.01$).

Long-term (1997–2000) distributions

In 1997, *C. obstrictus* was relatively widespread throughout southern Alberta. Adults were collected in flowering canola from a region approximately as far north as Brooks (50°35′N, 111°53′W), and infestations occurred south to the United States border (Fig. 2). The eastern range extended to approximately 120 km west of the Alberta–Saskatchewan border. Highest infestations occurred from Lethbridge south to the

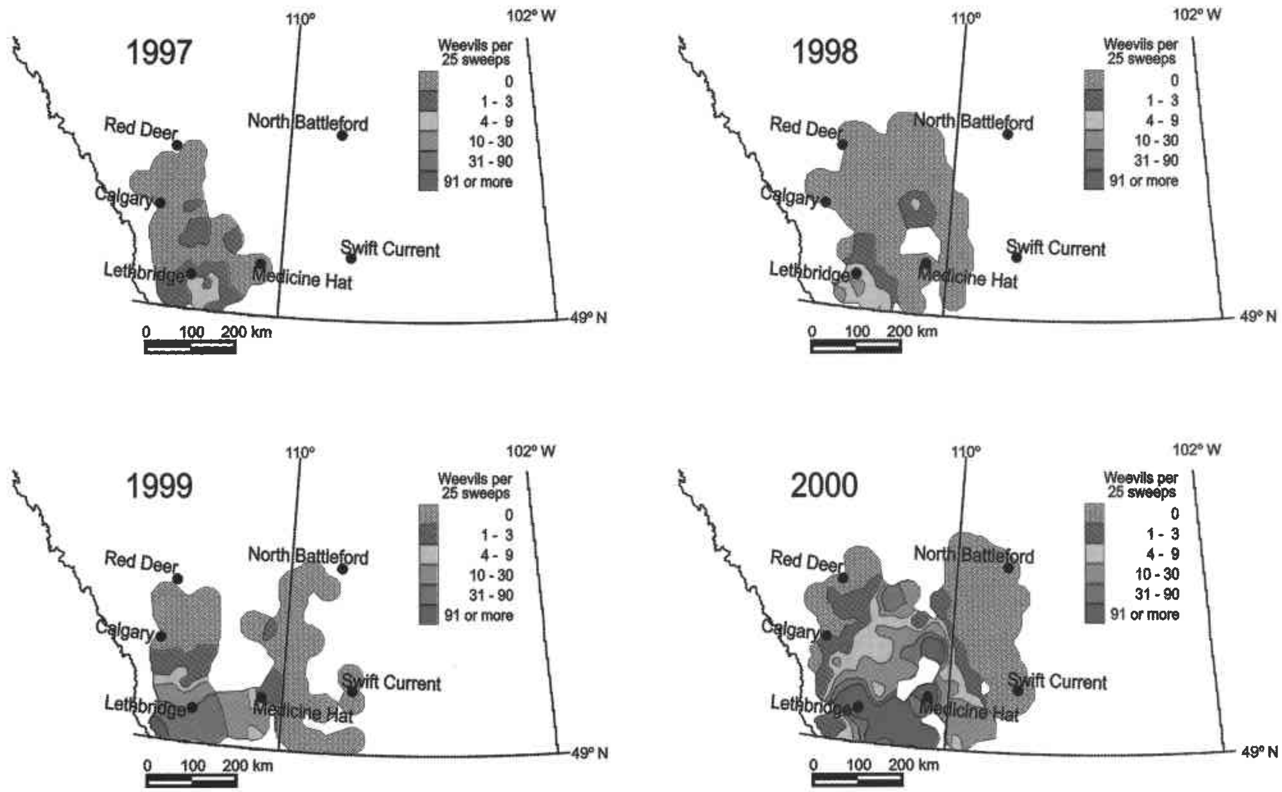

FIGURE 2. Distribution and abundance of *Ceutorhynchus obstrictus* in canola in Alberta and Saskatchewan, Canada, from 1997 to 2000. Maps were developed from field survey data (25 sweep net samples per field) using SPANS™.

United States border where population densities were approximately 0.5 weevils per sweep in some fields.

In 1998, *C. obstrictus* was relatively common throughout southern Alberta, and densities were similar to those observed in 1997 (Fig. 2). Infestations were most common in canola in the region extending south from Lethbridge to the United States border, but densities remained less than or equal to one adult per sweep. The northern range limit of cabbage seedpod weevil was approximately 50 km farther northward than in 1997 to near Hussar, Alberta (51°03′N, 112°41′W), but it was not found as far east as Medicine Hat, and no specimens were collected in Saskatchewan.

In 1999, the range of *C. obstrictus* increased farther northward than in 1998 by approximately 55 km, to near Oyen, Alberta (51°22′N, 110°28′W) (Fig. 2). Infestations were observed along the Alberta–Saskatchewan border at several locations, and although specimens were collected for the first time from Medicine Hat, only about 50 km west of the Saskatchewan border, the species range did not extend into Saskatchewan. Enormous population densities occurred in some fields in southern Alberta; densities of 10–15 weevils per sweep were relatively common in fields near Lethbridge and Taber (49°47′N, 112°08′W). As in previous years, greatest densities occurred in the region extending from Lethbridge to the United States border.

In 2000, the range and abundance of *C. obstrictus* continued to expand (Fig. 2). The range increased farther northward by approximately 70 km in east-central Alberta to near Big Valley (52°02′N, 112°46′W), and for the first time specimens were collected in southwestern Saskatchewan. Populations of 50–80 weevils per sweep occurred in southern Alberta fields near Grassy Lake (49°49′N, 111°43′W), Lethbridge, Taber, and Raymond (49°27′N, 112°39′W). Although cabbage seedpod weevil was first reported in fields near Medicine Hat only in 1999, by 2000 populations in this area had increased to densities of approximately 20 per sweep in some fields.

Climate model development (historical dataset)

The mean annual air temperature for Lethbridge from 1961 to 1990 was 5.6°C followed by Medicine Hat (5.5°C), Red Deer (2.3°C), and Peace River (0.7°C). Locality differences were greater during the winter months than during the growing season (Fig. 3). Mean monthly temperatures for Red Deer and Peace River were similar from May to August (Fig. 3, Table 2). In May, June, and July mean temperatures at the two locations differed by only 0.1–0.4°C. Mean air temperatures in Medicine Hat and Lethbridge were approximately 2.0–4.0°C warmer than in Red Deer and Peace River during the growing season (Fig. 3, Table 2).

Air temperatures early in the season (1 March – 30 April), when weevils begin to leave their overwintering sites, varied considerably between the sites. In Lethbridge, the mean monthly maximum temperature for March was 5.3°C, but the corresponding temperature for Peace River was –1.1°C (Table 2). These site differences decreased by May (19.3°C in Medicine Hat and 16.8°C in Peace River) (Table 2). The mean maximum daily temperature of 10°C was recorded in Medicine Hat near the end of the first week of April, but the corresponding temperature for Peace River occurred in mid- to late April.

Temperatures when *C. obstrictus* adults move to overwintering sites (1 September – 31 October), also varied among the Alberta sites. Mean monthly maximum temperatures in September in Lethbridge and Medicine Hat exceeded those in Red Deer and Peace River by 3–5°C (Table 2). Late-season temperatures at Peace River were consistently cooler than at the other three sites. In September, mean maximum temperatures at Peace River marginally exceeded the 15°C threshold temperature required by weevils for long flights (Dmoch 1965). By October, all four locations had mean maximum

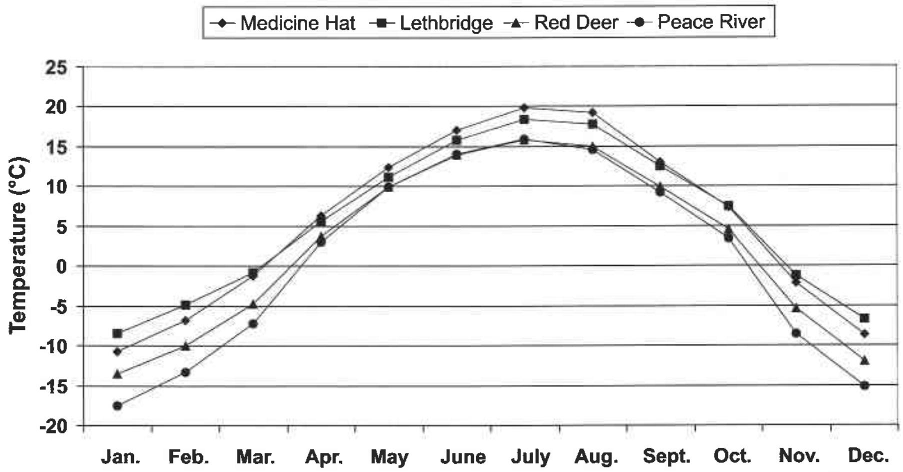

Figure 3. Long-term normal (1961–1990) mean monthly air temperatures for Medicine Hat, Lethbridge, Red Deer, and Peace River, Alberta.

Table 2. Long-term normal (1961–1990) monthly (March–October) maximum, minimum, and mean temperatures (°C) at Lethbridge, Medicine Hat, Red Deer, and Peace River, Alberta.

Location	Temperature	March	April	May	June	July	August	September	October
Lethbridge	Maximum	5.3	12.2	18.0	22.6	25.9	25.3	19.6	14.3
	Minimum	–6.9	–1.0	4.4	9.0	10.9	10.3	5.3	0.6
	Mean	–0.8	5.6	11.2	15.8	18.4	17.8	12.5	7.5
Medicine Hat	Maximum	4.7	13.0	19.3	24.0	27.3	26.8	20.3	14.4
	Minimum	–7.1	–0.4	5.5	10.1	12.2	11.4	5.6	0.2
	Mean	–1.2	6.3	12.4	17.1	19.8	19.2	13.0	7.3
Red Deer	Maximum	1.2	10.2	16.9	20.6	22.7	22.2	17.0	11.9
	Minimum	–10.8	–2.9	2.8	7.2	8.9	7.8	2.7	–2.8
	Mean	–4.7	3.7	9.9	14.0	15.8	15.0	9.9	4.6
Peace River	Maximum	–1.1	9.1	16.8	20.7	22.4	21.2	15.4	8.9
	Minimum	–13.3	–3.3	3.0	7.4	9.4	8.0	3.0	–2.2
	Mean	–7.2	3.0	9.9	14.1	15.9	14.6	9.2	3.4

temperatures below the 15°C threshold, and the mean monthly maximum temperature for Peace River was below 10°C (Table 2).

Climate model development (1997–2000)

During the growing season, defined here as the period of 1 May – 31 August inclusive, mean temperatures for 1997–2000 were similar in the four locations to long-term normal values (Table 3). Of these years, temperatures for 2000 most closely approximated long-term normals, whereas temperatures for the 1998 growing season, which were approximately 1.5°C warmer, deviated most strongly from these values. At Medicine Hat, mean temperatures for the growing season were 3.6 and 3.3°C warmer than Red Deer and Peace River, respectively (1997–2000). Mean growing season temperatures were similar in Peace River and Red Deer, with Peace River slightly warmer in 1998 and 1999 (Table 3).

Mean maximum temperatures for the period of 1 March – 30 April inclusive deviated more strongly from long-term normal mean maximum values than did mean

TABLE 3. Mean temperatures (°C) in 1997–2000 *versus* long-term normal values from the period of 1961–1990 at Medicine Hat, Lethbridge, Red Deer, and Peace River, Alberta.

Biological event	Location	1997	1998	1999	2000	1997–2000	Long-term normal
	Mean temperature during the growing season from 1 May to 31 August inclusive						
Canola growing season	Medicine Hat	17.1	18.2	15.9	17.4	17.2	17.1
	Lethbridge	16.0	17.1	15.0	15.7	16.0	15.6
	Red Deer	13.6	15.4	12.6	12.9	13.6	13.7
	Peace River	13.7	16.4	13.4	12.2	13.9	13.6
	Mean maximum temperatures from 1 March to 30 April inclusive						
Weevils leave overwintering sites	Medicine Hat	11.6	13.8	13.3	13.4	13.0	12.3
	Lethbridge	11.0	13.1	13.0	13.0	12.5	11.8
	Red Deer	7.5	12.3	9.3	9.5	9.7	9.4
	Peace River	6.0	12.2	9.2	8.0	8.9	8.3
	Mean maximum temperatures from 1 September to 31 October inclusive						
Weevils migrate to overwintering sites	Medicine Hat	22.0	22.9	20.9	21.2	21.8	20.5
	Lethbridge	20.9	22.6	20.2	20.7	21.1	19.4
	Red Deer	17.1	19.1	17.3	16.8	17.6	17.0
	Peace River	14.6	17.2	17.0	13.6	15.6	15.2

growing season temperatures (Table 3). In 1997, mean maximum temperatures in spring were lower at all sites than the long-term normals, but in 1998 mean maximum temperatures exceeded long-term normal values at all sites. The 1999 and 2000 spring periods were slightly warmer but closer to long-term normals than in 1997 or in 1998. Mean maximum spring temperatures at Medicine Hat for 1997–2000 were only 0.5°C warmer than at Lethbridge, but 3.3 and 4.1°C warmer than Red Deer and Peace River, respectively (Table 3).

Mean maximum temperatures for the period of 1 September – 31 October inclusive were warmer in 1997–2000 than long-term normal mean maximum values (Table 3). In 1998 this period was the warmest of the 4 years at all sites. Mean maximum temperatures for Lethbridge and Medicine Hat exceeded long-term normal values in 1997–2000 inclusive. When averaged over 1997–2000, temperatures in Medicine Hat were only 0.7°C warmer than Lethbridge, but 4.2 and 6.2°C warmer than Red Deer and Peace River, respectively. At Red Deer, 2000 was the only year with mean temperatures less than long-term normals. At Lethbridge and Medicine Hat, mean maximum temperatures did not drop below the 15°C threshold for long flights of *C. obstrictus* until mid-October (1997) to late October (1998–2000). At Red Deer, mean maximum temperatures dropped below 15°C between late September (1999, 2000) and early October (1998). At Peace River, temperatures dropped below 15°C between mid-September (2000) and late September (1998, 1999).

CLIMEX™ model predictions and validation

EI values calculated with CLIMEX™ for the 193 meteorological stations in western Canada ranged from 0 to 41. The mean EI was 31.2. Of the stations, 185 had EI values greater than 20. EI values for Medicine Hat, Lethbridge, Red Deer, and Peace River were 38, 33, 28, and 29, respectively.

The map produced with SPANS™ for the EI values generated with CLIMEX™ indicated that the entire region of canola production in western Canada had EI values predicted to be suitable for *C. obstrictus* (Fig. 4). The model predicted that southern Manitoba, from the interlake region to the United States border, where EI values ranged from 35 to 40, was favorable for establishment, reproduction, and development of *C. obstrictus*. The model also predicted that most of southern and central Saskatchewan were highly suitable for establishment of this pest, with EI values ranging from 30 to 35. Northwestern Alberta near Grande Prairie (55°10′N, 118°48′W), west-central Alberta near Red Deer, northeastern Alberta near Bonnyville (54°16′N, 110°44′W), and southwestern Saskatchewan near Maple Creek (49°55′N, 109°27′W) were less suitable for successful establishment of *C. obstrictus*, with EI values ranging from 20 to 30. CLIMEX™ predicted that the region of Alberta corresponding generally to the foothills of the Rocky Mountains was least suitable to successful establishment of this pest, with EI values ranging from 0 to 20 (Fig. 4).

The model was validated by comparing predicted EI values with observed densities of *C. obstrictus* from adult surveys. Because the 2000 meteorological data were closer to long-term normal values than those of the other 3 years, the CLIMEX™ map should be similar to the 2000 survey map. The CLIMEX™ map of EI values corresponded well with the 2000 weevil survey map. Differences between the two figures represent differences between potential distribution and abundance based on long-term meteorological data (Fig. 3) and actual survey results for 2000 (Fig. 2). The EI values for Red Deer and Peace River are approximately 15% less than Lethbridge and 25% less than Medicine Hat; in general, survey results recorded similar differences in infestation levels among these sites.

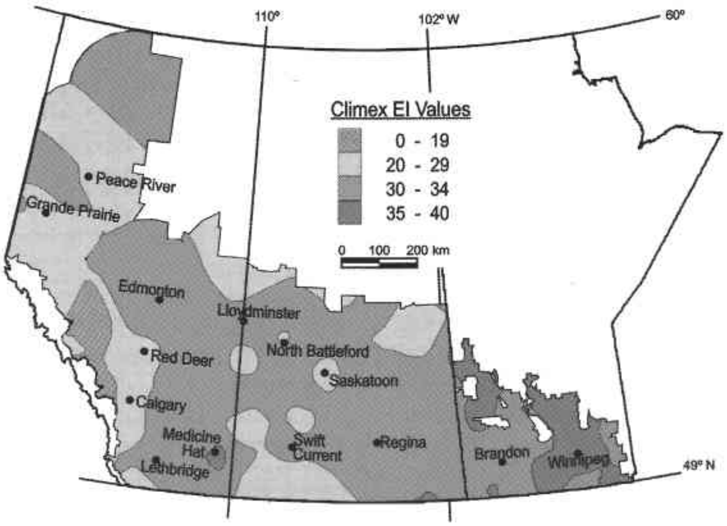

FIGURE 4. Predicted distribution and abundance of *Ceutorhynchus obstrictus* in western Canada. Ecoclimatic Index (EI) values were developed with CLIMEX™, and the map was generated using SPANS™. EI values describe the suitability of specific locations for survival and reproduction, where EI values greater than or equal to 20 are favorable for species establishment and survival but values less than 20 indicate marginal or unfavorable sites.

Discussion

Short-term temporal distributions of *C. obstrictus* adults are consistent with important assumptions incorporated in our field survey methods and have implications for population monitoring. After invading canola crops, adults occur predominantly in the inflorescence, regardless of time of day (Fig. 1). Sampling of canola in bud and flower to estimate population densities can therefore be performed at any time of day, at least in calm, clear conditions, unlike monitoring for some other pest species that alter their positions over time. Surveys conducted in this study were not restricted to sampling at specific times of day, only when winds were calm and crops were in flower; however, the behavioural tendency of weevils to remain in the inflorescence would have minimized sampling variation.

Our surveys to monitor geographical changes in the distribution and abundance of the cabbage seedpod weevil have indicated rapid dispersal of this species. From 1997 to 2000, *C. obstrictus* extended its range northward and eastward at a rate of approximately 55 km/year. Great increases in density were associated with these range extensions. For example, flowering canola fields approximately 50 km south of Lethbridge harbored densities of approximately one adult weevil per sweep in 1997 and 1998, but by 2000, some fields in the same area had densities of 80–120 weevils per sweep.

Synthesis of meteorological and biological data through application of the CLIMEX™ model suggests that the potential range of *C. obstrictus* includes the entire region of canola production across the three prairie provinces of Canada, and that the weevil has the potential to become abundant over this range. Now that the species is well established in the Prairie ecozone, having survived and increased in abundance over the past 5 years in southern Alberta, no substantial geographical barriers exist to prevent its spread throughout Canada's primary region of canola production. The only relevant potential geographical barriers include the Saskatchewan River system and a region of coniferous forest encompassing approximately 150 km^2 in northwestern Alberta separating canola fields of the Peace River agricultural region from those in west-central Alberta. Of these, the Saskatchewan River system presents the least significant barrier because the average widths of the North and South Saskatchewan Rivers are only about 300 and 200 m, respectively (although this may vary somewhat with discharge) (Byfield 1984), and the river valleys provide habitat for several brassicaceous host plant species (Budd and Best 1969). Although some Brassicaceae also occur throughout the coniferous forest region separating canola fields in the Peace River region from those in west-central Alberta (Moss 1959), the distance separating the two areas of canola cropping (about 150 km^2) would slow or possibly prevent dispersal of *C. obstrictus*.

Comparisons of meteorological data for different sites in Alberta with the physiological requirements of *C. obstrictus* indicate that once its maximum dispersal range is reached, the timing of some biological activities will vary over the geographic expanse of the province. For example, movements from overwintering sites, which occur when daily maximum temperatures reach 9–11°C (Dmoch 1965), would begin in early April in southern Alberta but approximately 2 weeks later in Red Deer and Peace River. Meteorological data indicate that initial weevil activity at Lethbridge occurred from late March (1999) to mid-April (1997) and the period of long flight occurred from mid-April (1998) to early May (1997). Initial flight activity and long flights occurred approximately 1 week earlier in Medicine Hat. In Red Deer, initial flight activity was just beginning when this activity was completed in the two southern locations. Should the species range eventually extend to Peace River, initial activity would occur between mid- and late April, and long flights between mid-April and June.

Environmental conditions in the 1997–2000 growing seasons were generally similar to long-term normal values, but late-season temperatures were warmer than normal (Table 3). A return to late-season temperatures that more closely approximate long-term normal values could negatively affect population densities of *C. obstrictus*. In autumn, adults feed extensively on host plants (Dosdall and Dolinski 2001), presumably to build up the fat reserves required to overwinter. The effect of cool temperatures late in the season, which would limit flight activity to feeding sites and perhaps advance migration to overwintering sites, could reduce overwintering success or the potential for population growth.

Although some parameters used in the model were based on extensive research (*e.g.*, periods of flight activity of *C. obstrictus*), other parameter values were not precisely known and input values were estimated (*e.g.*, larval developmental rate, overwintering temperature requirements). It could therefore be argued that the inherent error from estimating such parameters with CLIMEX™ would result in inaccurate or misleading predictions; however, Worner (1988) found that response parameters of CLIMEX™ are not overly sensitive, so changing these input values do not have a great impact on results. Our model determined EI values that substantially exceeded those where ecoclimatic conditions were considered marginal, and these applied to vast areas of western Canada, particularly in southern Manitoba (Fig. 4). It is therefore probable that this pest will greatly expand its range, although the final limits of its distribution will remain unknown for several years.

Several factors can affect the establishment success of species introduced to new regions, including previous invasion success, habitat availability, and the similarity of the climate to the traditional range of the species (Williamson 1996; Venette and Carey 1998). These factors are based on the concept that species with broad physiological tolerances are more likely to invade environments that are climatically variable, but species with narrow tolerances are likely to invade stable environments (Venette and Hutchison 1999). CLIMEX™ follows the premise that the potential range of a species is determined primarily by abiotic conditions, principally climatic suitability (Venette and Hutchison 1999); however, biotic factors also have great importance in affecting the abundance of insect populations (Dent 2000). For *C. obstrictus*, natural enemies and the spatial distributions of host plants could potentially limit its dispersal and abundance. In western Canada, host plant availability is not expected to limit the distribution of cabbage seedpod weevil because approximately 4 million ha of *B. napus* are grown annually in this region (Canola Council of Canada 2001) and brassicaceous weed species like wild mustard, *Sinapis arvensis* L., can serve as alternate hosts and are abundant throughout several ecozones (Dmoch 1965; Frankton and Mulligan 1970). Although several parasitoid species are important for reducing weevil populations in Europe and the United States (Dmoch 1965; Herting 1973; Harmon and McCaffrey 1997), to date, parasitism has had a minor impact on its populations in southern Alberta. A species of Braconidae (Hymenoptera) was found to attack a small percentage of weevil adults in commercial fields near Lethbridge (Dosdall *et al.* 2001). Recently evidence was discovered of a pteromalid ectoparasite (Hymenoptera) attacking cabbage seedpod weevil larvae within canola pods (LM Dosdall, unpublished data); however, it occurs rarely and so far infests only a minor segment of the weevil population. If parasitoid populations increase in numbers and disperse throughout the range of the weevil or are introduced in biocontrol programs, the rate of dispersal of *C. obstrictus*, and perhaps the extent of its eventual range, may be reduced.

According to the CLIMEX™ model developed here, the predicted range of *C. obstrictus* could eventually encompass some 5 million ha of canola cropland in western Canada. The economic and environmental implications of this invasion are enormous because application of broad-spectrum chemical insecticide is currently the only control strategy available to canola producers (Dosdall *et al.* 2001). Results of this study emphasize the importance of developing new, alternative control strategies for this pest that can minimize its economic impact and enhance environmental sustainability.

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References

Baker WW. 1936. Notes on a European weevil, *Ceutorhynchus assimilis* Payk., recently found in the state of Washington. *The Canadian Entomologist* **68**: 191–3

Bonnemaison L. 1957. Le charançon des siliques (*Ceutorhynchus assimilis* Payk.) biologie et méthode de lutte. *Annales des Epiphytes* **4** : 387–543

Brodeur J, Leclerc L-A, Fournier M, Roy M. 2001. Cabbage seedpod weevil (Coleoptera: Curculionidae): a new pest of canola in northeastern North America. *The Canadian Entomologist* **133**: 709–11

Budd AC, Best KF. 1969. Wild plants of the Canadian Prairies. *Canada Department of Agriculture Research Branch Publication* **983**

Buntin GD, McCaffrey JP, Raymer PL, Romero J. 1995. Quality and germination of rapeseed and canola seed damaged by adult cabbage seedpod weevil, *Ceutorhynchus assimilis* Paykull (Coleoptera: Curculionidae). *Canadian Journal of Plant Science* **75**: 539–41

Byfield T (*Editor*). 1984. *The atlas of Alberta*. Edmonton, Alberta: Interwest Publications Ltd

Canola Council of Canada. 2001. Canola. *Canola Council of Canada Publication* **6500**

Cárcamo HA, Dosdall L, Dolinski M, Olfert O, Byers JR. 2001. The cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Coleoptera: Curculionidae)—a review. *Journal of the Entomological Society of British Columbia*. **98**: 201–10

Carlson EC, Lange WH Jr., Sciaroni RH. 1951. Distribution and control of the cabbage seedpod weevil in California. *Journal of Economic Entomology* **44**: 958–66

Dent, D. 2000. *Insect pest management. 2nd edition*. Wallingford, Oxon, United Kingdom: CABI Publishing

Dmoch J. 1965. The dynamics of a population of the cabbage seedpod weevil (*Ceutorhynchus assimilis* Payk.) and the development of winter rape. Part I. *Ekologia Polska Seria A* **13**: 249–87

Dosdall LM, Dolinski MG. 2001. Biology and control of the cabbage seedpod weevil, a new pest of canola in Alberta. *Alberta Agriculture, Food and Rural Development Technical Report*

Dosdall LM, Moisey D, Cárcamo H, Dunn R. 2001. Cabbage seedpod weevil factsheet. *Alberta Agriculture, Food and Rural Development Agdex* **622-21**

Frankton C, Mulligan GA. 1970. Weeds of Canada. *Canada Department of Agriculture Publication* **948**

Hanson AJ, Carlson EC, Breakey EP, Webster RL. 1948. Biology of the cabbage seedpod weevil in northwestern Washington. *State College of Washington Agricultural Experiment Station Bulletin* **498**. Pullman, Washington: State College of Washington

Harmon BL, McCaffrey JP. 1997. Parasitism of adult *Ceutorhynchus assimilis* (Coleoptera: Curculionidae) by *Microctonus melanopus* (Hymenoptera: Braconidae) in northern Idaho and eastern Washington. *Journal of Agricultural Entomology* **14**: 55–9

Harper FR, Berkenkamp B. 1975. Revised growth-stage key for *Brassica campestris* and *B. napus*. *Canadian Journal of Plant Science* **55**: 657–8

Herting B. 1973. A catalogue of parasites and predators of terrestrial arthropods. Section A. Host or prey/enemy. Volume III. Coleoptera and Strepsiptera. Wallingford, Oxon, United Kingdom: Commonwealth Agriculture Bureau

Hoffman A. 1954. Coleopteres Curculionides: *Ceutorhynchus assimilis* Paykull. *Faune de France* **59**: 994–7

Kjær-Pedersen C. 1992. Flight behaviour of the cabbage seedpod weevil. *Entomologia Experimentalis et Applicata* **62**: 61–6

Kozlowski MW, Lux S, Dmoch J. 1983. Oviposition behaviour and pod marking in the cabbage seed weevil, *Ceutorhynchus assimilis*. *Entomologia Experimentalis et Applicata* **34**: 277–82

Maywald GF, Sutherst RW. 1987. Ecological models I. Assessing climatic favourability with CLIMEX. pp 68–71 *in* RW Sutherst (Ed), Ticks and tick-borne diseases. *ACIAR Proceedings* **17**: 68–71

McCaffrey JP. 1992. Review of US canola pest complex: cabbage seedpod weevil. pp 140–3 *in* Proceedings of the 1992 US Canola Conference, Washington, DC, 5–6 March 1992. Memphis, Tennessee: Ameri-Can Pedigree Seed Co

McLeod JH. 1962. Cabbage seedpod weevil—*Ceutorhynchus assimilis* (Payk.) Curculionidae. pp 5–6 *in* JH McLeod, BM McGugan, HC Coppel (Eds), A review of the biological control attempts against insects and weeds in Canada. Farnham Royal, Bucks, England: Commonwealth Agricultural Bureaux (CAB)

Moss EH. 1959. *Flora of Alberta*. Toronto, Ontario: University of Toronto Press

Mudd A, Ferguson AW, Blight MM, Williams IH, Scubla P, Solinas M. 1997. Extraction, isolation, and composition of oviposition-deterring secretion of cabbage seed weevil *Ceutorhynchus assimilis*. *Journal of Chemical Ecology* **23**: 2227–40

Ni XZ, McCaffrey JP, Stoltz RL, Harmon BL. 1990. Effects of postdiapause adult diet and temperature on oogenesis of the cabbage seedpod weevil (Coleoptera: Curculionidae). *Journal of Economic Entomology* **83**: 2246–51

Olfert O, Chapco W. 2001. Analysis of historical surveys and genetic diversity of grasshopper populations to assess risk. Integrated Management of Crop Land Pests – Final Technical Report for Canada/Saskatchewan Agri-Food Innovation Fund. [Available from Saskatoon Research Centre, Agriculture and Agri-Food Canada, 107 Science Place, Saskatoon, Saskatchewan, Canada S7N 0X2]

SAS Institute Inc. 1990. *SAS system for personal computers, release 6.04*. Cary, North Carolina: SAS Institute Inc

Sutherst RW. 1991. Predicting the survival of immigrant insect pests in new environments. *Crop Protection* **10**: 331–3

Sutherst RW, Maywald GF. 1985. A computerized system for matching climates in ecology. *Agriculture Ecosystems and Environment* **13**: 281–99

Sutherst RW, Maywald GF, Yonow T, Stevens PM. 1988. *CLIMEX for Windows, version 1.1*. Brisbane, Australia: Co-operative Research Centre for Tropical Pest Management

Venette RC, Carey JR. 1998. Invasion biology: rethinking our response to alien species. *California Agriculture* **52**: 13–7

Venette RC, Hutchison WD. 1999. Assessing the risk of establishment by pink bollworm (Lepidoptera: Gelechiidae) in the southeastern United States. *Environmental Entomology* **28**: 445–55

Williamson M. 1996. *Biological invasions*. New York: Chapman and Hall

Worner SP. 1988. Ecoclimatic assessment of potential establishment of exotic pests. *Journal of Economic Entomology* **81**: 973–83

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