

**DETERMINING FLIGHT BEHAVIOUR IN THE
EUROPEAN WIREWORMS**
Agriotes lineatus and *A. obscurus*

by

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ABSTRACT

Introduced European wireworms *Agriotes lineatus* and *A. obscurus* are increasingly serious and destructive pests of many field crops in British Columbia. Previous studies focused on the larval life stage, but information on adult biology is lacking and important for developing sound management strategies. Flight behaviour in *Agriotes lineatus* and *A. obscurus* was unknown in North America, thus potential exclusion of the insects using physical barriers was being investigated. I tested the hypothesis that both species were capable of flight under specific temperature conditions and made both laboratory and field observations on flight and ground dispersal. Laboratory experiments induced flight behaviour at a minimum ambient air temperature of 25°C, corresponding to beetle surface temperatures of 26 °C ($\pm 1.0^\circ\text{C}$) from direct insolation. Field observations recorded flight activity in males and females of both species. Flight may be primarily in response to avoidance of desiccation.

Key words: *Agriotes lineatus*, *A. obscurus*, flight behaviour, British Columbia, insolation

DEDICATION

To Mom and Dad:

Thank you for the infinite support and confidence in me.

To my wife Brenda, and son Andrew; who make it all worthwhile.

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1.0 INTRODUCTION

1.1 Description of Click Beetles and Wireworms

European click beetles belong to the genus *Agriotes* Eschscholtz (Coleoptera: Elateridae), and three of these species have been introduced into Canada. In British Columbia (BC), the dusky wireworm, *Agriotes obscurus* L., and the lined click beetle, *A. lineatus* L., were introduced more than a century ago (Wilkinson 1963; Vernon *et al.* 2001), and have become important economic pest species in several crops. In Atlantic Canada, these and an additional European wireworm, *A. sputator* L. have become the dominant economic species (Eidt 1953).

Wireworms are narrow, cylindrical, smooth and leathery, thus earning their common name of wireworms. Larval colouration is generally yellow-to-amber with a darkened head and having three paired legs on the segments just posterior the head. Larvae increase in length from less than 2 mm to about 23 mm at maturity, and live for several years in the soil depending on the species (Glen 1944). The genus *Agriotes* is comprised of several species found in both North America and Europe. In *Agriotes*, the last or ninth segment of the body is tapered, with two small dark spots on the upper surface. These spots are one of the distinguishing features of *Agriotes* spp. wireworms (Glen 1944). The main European *Agriotes* species in BC, *A. obscurus* and *A. lineatus*, are very difficult to differentiate in their larval form (Wilkinson 1963).

The adult click beetles are named for the audible clicking sound produced when overturned. This clicking behaviour is used to put the insect on its feet should it become

lodged on its back. Click beetles are elongated and oval in shape, and are dark brown to chestnut brown in colour. Size varies according to species, however *A. obscurus* and *A. lineatus* are 8 to 10 mm in length. *A. lineatus* is typically more slender or cigar shaped than *A. obscurus*, which is broader across the abdomen. *A. lineatus* is further differentiated by the presence of lighter brown ridges running parallel to the body along the surface of the elytra, where its common name, the lined click beetle is derived. *A. obscurus* is commonly named the dusky click beetle for its uniform dark brown appearance.

1.2 Life Histories

Adult click beetles emerge from over wintering cells in early spring as soon as the soil warms to about 10 degrees Celsius. In the Fraser valley of BC, this usually occurs from mid to late March (Vernon *et al.* 2001). After mating, egg laying takes place in early May to mid June. Fields that are in sod, red clover, or cereals are favoured locations for oviposition (Fox 1973), and eggs are laid singly or in clusters just beneath the soil surface (Crozier 2000). The eggs require approximately three weeks to hatch into small neonate larvae, and hatching occurs over an extended period of time. The newly hatched larvae feed solely on living vegetation such as the roots of grasses and other crops to survive and mature (Furlan 1998). Feeding continues until fall when larvae move deeper into the soil to over winter. The larvae resume feeding the following spring and summer while growing considerably. This larval growth cycle continues for three to four years. Due to overlaps in generations, and variability in growth rates, all sizes can usually be found at any one time in fields of mature pasture. Pupation occurs in earthen cells during late July and early August. During the pupal stage, which lasts from about

the third week in July to the second week in August, pupae are fragile and easily injured by cultivation. The adult stage develops in pupal cells in soil and adults may remain in this cell over winter or leave the cell to over winter in the soil.

1.3 Damage

Wireworms, which primarily feed underground, can cause catastrophic losses to crops due to stand and yield reduction (i.e. cereals, forages, vegetables, small fruits, ornamentals) and/or cosmetic injuries (i.e. carrot, strawberry, potato)(Wilkinson 1963; Vernon 2005). Typically, wireworm problems are most severe in fields that have had a recent history of pasture or cereal crops, since these are the preferred hosts for wireworms, and are targeted oviposition sites for adult click beetles (Fox 1973). When these crops are removed, wireworms remaining in the field will feed on many higher value crops planted in rotation, and due to their long life cycles (2-6 years depending on the species), damage by wireworms can continue for several years (Eidt 1953, Parker and Seeney1997, LaGasa 2006).

Wireworms feed on roots and germinating seeds of grasses and other plants and are attracted to the carbon dioxide produced as a bi-product of cellular respiration (Doane *et al.* 1975). Considerable direct economic loss occurs due to the destruction of seed or seedlings, especially in cereals, corn and vegetable crops (Eidt 1953, Parker and Seeney1997, LaGasa 2006). Cosmetic damage occurs in crops such as potato, ginseng or rutabagas, where damage appears as pits, scars or holes bored straight into the edible roots or tubers. This damage results in a lowered grade or unmarketable crop (Parker and Seeney 1997). The two European wireworms, *A. lineatus* and *A. obscurus*, have been

responsible for considerable damage to potatoes in the Fraser valley of BC (Vernon *et al.* 2001).

1.4 Pest History

European wireworms, *A. lineatus* and *A. obscurus*, were discovered in British Columbia in 1949 (King 1950) at Cobble Hill. Thought to have been introduced from Europe around 1900 (Wilkinson 1963), these European wireworm are considered among Europe's most widespread and destructive pests (Eidt 1953, Kudryavtsev *et al.*, 1993, Parker and Howard 2001). It is believed that *A. lineatus* and *A. obscurus* were introduced in North America in the 1800's. Infestations of these species, as well as *A. sputator* in Nova Scotia, were thought to have arrived through the dumping of wireworm-infested soil as ship ballast along major ports (Brown 1940). However the spread of *A. lineatus* and *A. obscurus* was initially slow, since infestations were confined by bodies of water and dense forests. Coupled with this physical barrier was the belief that the adult beetles were incapable of flight (Wilkinson *et al.* 1976, Eidt 1953) limiting their ability to spread over a large area quickly. Since the 1980's, however, these pests have substantially increased their range in both the Fraser valley of BC and Nova Scotia, which was due in part to increased opportunities for spread, including expanded and contiguous farmland and increased movement of wireworm infested soil through turf and nursery transportation (Wilkinson 1980, Vernon *et al.* 2001).

1.5 Control Options

Historically in North America, wireworms had been controlled by a variety of organochlorine insecticides and until the early 1990's by organophosphate insecticides (Vernon *et al.* 2001). In the 1940's, growers were able to achieve excellent long term wireworm control at a cost of \$1 to \$6 a hectare using such products as Ethylene dibromide (EDB) Benzene hexachloride (BHC) and Dichloro-diphenyl trichloroethane (DDT) (King *et al.* 1948). While achieving adequate control and reducing the impact of wireworms on agriculture, this sole reliance on chemical control lead to several problems. The most popular formulations of organophosphate insecticides were in a granular form that was incorporated into the soil. This proved lethal to waterfowl in areas that were major flyways of migratory birds because the granular formulation was easily ingested in sufficient quantities to cause toxicity. Dead and dying waterfowl were then preyed upon by raptors thus bio-accumulating the toxin and causing mortality to these important predators (Wilson *et al.* 2002). In light of the risk to birds, the registered use of such products have been discontinued by governing agencies and further use voluntarily curbed in all areas by the removal of such products from the market by the product registrant. De-registration of other organophosphate products has lead to an extremely limited number of effective chemical controls still available to producers. This shift in control strategy has caused increased interest in cultural, biological and physical tactics to manipulate and achieve effective control of the wireworm pest. To develop strategies that best achieve the goal of limiting wireworm damage, it is necessary to fully understand the biology of the European wireworm and to discover potential areas of

weakness where the life cycle or behaviour of the insect can be exploited to gain control of the pest.

1.6 Flight Behaviour

Determining whether flight is used by these species as a form of territorial expansion is important. The adult stage is the most mobile which determines species range and rate of spread. Any control achieved with adult beetles before egg laying has the potential to significantly decrease the number of eggs that give rise to the next generation of wireworms. It is therefore of practical importance to understand the biology of these pests to apply appropriate control measures that will be most efficacious. Study of click beetle flight behaviour is important because it can be used to determine distribution and spread of wireworm infestations, identify specific or local conditions under which these insects are capable or incapable of flight. This information will help identify potential time points, during which maximum control might be taken utilizing a variety of techniques such as mass trapping, pheromone mating disruption, optimum trap placement or physical barrier placement.

2.0 FLIGHT ACTIVITY OF *AGRIOTES LINEATUS* L. AND *A. OBSCURUS* L. (COLEOPTERA: ELATERIDAE) IN THE FIELD

2.1 Historical Reports

Since their discovery in British Columbia (King 1950, Lane 1952) and the Maritimes (Eidt 1953), it has been stated that *A. lineatus* and *A. obscurus* populations in Canada do not fly (Eidt 1953, Wilkinson *et al.* 1976), although flight activity in both species has been reported from Europe (Subklew 1935, Fryer 1941, Brian 1947). This is an important consideration, because the efficacy of various prospective control methods (e.g. mass trapping, mating disruption and physical exclusion), would be affected by flight activity. This chapter describes a number of independent observations made under field conditions in the lower Fraser valley of BC in 2001 and 2002, which verify that flight activity occurs in both *A. lineatus* and *A. obscurus*.

2.2 Flight behaviour observations

Agassiz, 2001: In a one-hectare fallow field in Agassiz, British Columbia, a ground-based Vernon beetle trap (PheroTech Inc. Delta, BC) (Vernon *et al.* 2001) baited with *A. obscurus* pheromone (LaGasa *et al.* 2000) was inspected at 15:30 on 22 May, 2001. The temperature at that time was 28 °C, with only a slight breeze. The contents of the trap, which consisted only of 85 male *A. obscurus* were placed in an open metal pan (22.5 x 37.5 x 3.8 cm). Although most beetles were dead due to prolonged exposure to heat

within the extremely hot black trap, a number were still quite active. One beetle climbed onto a film vial in the pan, spread its elytra and took flight. It flew about 3 m to the east, then turned and gained altitude from 1 m to 2 m and flew west, at one point flying about 2.5 m high. The beetle flew for about 30 m at which point it was caught in mid air about 2 m above ground and saved for positive identification. The specimen was a male *A. obscurus* (Crozier *et al.* 2003)

Ladner, 2002: Several beetles were observed in flight on 12 May 2002 between the hours of 12:30 and 15:30 PST. The flight observations occurred in a one-hectare field of pasture surrounded by approximately 20 hectares of tilled agricultural land in Ladner, British Columbia. The temperature, which was 24°C at 1200h PST at the Vancouver International Airport had dropped to 19°C by 1800h. Other weather conditions included: prevailing winds at 13 km per hour from the west; no cloud cover; relative humidity of 64%; and barometric pressure at 101.79 kpa and dropping during this period. The field directly west of the pasture was in the process of being cultivated, and at least twenty click beetles were observed to be flying toward the pasture from that direction. A number of the click beetles in flight were captured, tentatively identified in the field and voucher specimens subsequently identified in the laboratory as a mixture of *A. lineatus* and *A. obscurus*.

When the thick grass of the pasture was also inspected, large numbers of *A. lineatus* and the occasional *A. obscurus* (about 5 to 10 beetles per square meter) were observed crawling up blades of grass, raising their elytra and taking flight. Out of 20

beetles captured on grass leaves, every beetle was capable of escaping from open hand via flight.

Flights were best described as direct and deliberate with little to no side-to side deviation as commonly observed in certain lepidopterans (Southwood *et al.* 1974). Beetles taking flight from grass obtained altitudes up to 4 m with the majority flying between 1 to 2 m in height and travelled approximately 5-10 km per hour in an easterly direction with the wind. Distance covered while flying ranged from less than 1 m to 100 m on one occasion, with an average flight covering a distance of 2-3 m (n=20). Twelve beetles were intercepted mid-flight on clothing while traversing the pasture. The captured specimens were confirmed (by R. Vernon) as *A. lineatus* males (6) and females (2) and *A. obscurus* males (4).

Flight behaviour was again observed on 24 May 2002 between 14:30 and 17:00 PST. Temperatures ranged from 16 -17°C during this period under scattered cloud with westerly winds at 7 km/h and relative humidity between 46% to 56%. Flight activity was not as prevalent as on 12 May, with only eight beetles being observed in flight. Most flights appeared to occur in random directions within the pasture, with no beetles being observed to enter or exit from the surrounding fallow fields. Six beetles were captured in flight and positively identified (by R. Vernon).as male *A. lineatus* (5) and male *A. obscurus* (1).

Surrey, 2002: Both male and female *A. obscurus* and *A. lineatus* were observed in flight between 13:00 and 17:00 PST on 12 May 2002 in south Surrey, B. C. Male and female *A. obscurus* and *A. lineatus* were captured in flight via sweep net and preserved as

voucher specimens. The flight activity coincided with the first warm day of the beetle emergence period (R.S. Vernon, unpublished data), at a temperature of approximately 26°C under sunny skies. Beetles were observed climbing blades of grass on recently cut lawn. Successful flight from the grass usually took several attempts and short flights in the vicinity of 10 cm were common. With longer flights, beetles rose at a constant velocity up and out of the yard at altitudes of 1 to 4 m. A single male *A. lineatus* successfully took off from the lawn, gained an altitude of about 1 m, descended towards a deciduous shrub and circled a horizontal branch before landing on the upper side. Closer inspection revealed the presence of an *A. lineatus* female 5 cm from the landing site. At 16:00 PST, an average density of four click beetles/ 0.09 m² of lawn was recorded. By around 17:00 PST, flight activity had mostly ceased. Beetles were searched for daily throughout the rest of the summer, but were never observed in mass flight again. Of 20 beetles captured in flight, 6 male and 5 female *A. obscurus* were positively identified in the lab (R. Vernon). Females frozen and dissected later were found to contain eggs in good condition (Crozier *et al.* 2003). These data indicate that indeed these species can disperse using flight, which may allow for a wider distribution. However the distances observed were not significant enough to suggest vast migratory dispersals during single seasons.

2.3 Ground Dispersal

To obtain a clearer picture of the potential for dispersal by *A. lineatus* and *A. obscurus*, it is also important to determine the ability of the click beetle to travel over land by walking, as this is likely their dominant mode of transportation. If adults'

primary mode of transportation is walking, physical barriers such as forest blocks, mixed cropping or temporal rotational cropping (Boiteau 2005) may be helpful in reducing spread and /or re-infestation from surrounding headlands.

In a preliminary study to estimate their speed of walking, beetles were placed at the centre of a calibrated wooden dowel and timed as they walked to a distance of 0.50m. Two temperature regimes were tested in the lab; 22°C as a base temperature and 27°C achieved with the use of an infrared heat lamp. These temperatures were chosen to simulate differences in temperatures encountered by the insects on overcast and clear bright days. Twenty *A. lineatus* and thirteen *A. obscurus* insects were measured in both temperature regimes. Both *A. lineatus* and *A. obscurus* had a mean velocity of 0.007m/s at 22°C, and mean velocities of 0.013 and 0.012m/s, respectively, at 27°C. Differences in velocity between the two species were not significantly different ($P>0.05$, Tukey's Studentized Range test (Zar 1984)).

Maximum Travel Distance per Day observations:

Beetle movement on a dowel in a laboratory is an oversimplified measure of actual field conditions. Hence a marked release-recapture observation was undertaken to try to calculate the speed at which the adult click beetles could travel under field conditions. A pheromone source was used as bait for recapture because I assumed that this source would provide the greatest directional motivation as long as winds remained from the predominant direction. Eighty male *Agriotes lineatus* were marked on the thorax with white acrylic paint and placed 50 m downwind (west) from the central pheromone trap within a field located in Ladner, British Columbia. The field had been

planted with potato and the crop was just starting to break the surface. The field was devoid of weeds and a thin dry crust of soil on the surface provided little to no shelter from the elements. The beetles were released at 0800h PST, 31 May 2002, at which time a 16 km/h wind was blowing from the east and the temperature under cloudy skies was 17°C (Environment Canada 2006). The trap was examined at 8:00 PST the following day, and seven marked beetles were found. During 1 June 2002, the temperature reached a high of 21°C but winds had shifted to the prevailing westerly direction at a speed of 14 km/h (Environment Canada 2006). The trap was subsequently checked over the next two days with no marked beetles being captured. Additional pheromone traps located 159 m and 164 m west from the release- recapture trap contained 5 and 8 marked beetles, respectively, on the third day after release. Total recapture of marked beetles (n=80) in all traps, therefore, was 25% after three days.

These data show that male *A. lineatus* beetles were capable of travelling 50 m over a 24-hour period. It is also likely that some or all of the seven beetles collected in the primary trap were captured earlier than 24 hours after release, and that they could have travelled beyond the 50 m primary trap if not captured. The data also suggest that beetles not collected in the primary trap may have lost the scent when the wind reversed direction on the second day, and picked up the new scent from the additional traps that would have been between 100 m (from beetle release point) and 150 m (from primary trap) away. The fact that they were then collected in the additional traps on the third day after release suggests that they had travelled 100-150 m over a three day period.

2.4 Flight speed calculations

Observations were conducted to calculate the flight speed of click beetles to compare them to literature values for other species. This would help to quantify the flight ability of these wireworms and provide an understanding of the biology and mechanics of click beetle flight. Observations occurred on 12 May 2002 in Ladner, British Columbia at the site previously described in section 2.2. Velocity was determined by measuring the distance flown from takeoff to landing and dividing the total distance flown by the duration of the flight in seconds with a stopwatch. Six beetles achieving flight were measured for *A. lineatus* (3 male, 1 female) and *A. obscurus* (2 males). A mean velocity of 1.40 m/s was achieved for the six flights over an average distance of 37.2m, with the *A. obscurus* flight speeds being within the highest and lowest range of *A. lineatus* which was 1.61m/s and 1.28m/s respectively.

2.5 Discussion

Chapman (1975) and Caprio and Grafius (1990) describe two categories of insect flight behaviour, known as trivial flight behaviour and migratory flight behaviour. Trivial flights are defined as those which typically are of short distance and duration but may show great variation depending on the species (Southwood 1962, Chapman 1975, Caprio and Grafius 1990). These types of flight are those that are commonly used by several species of insects to seek food, locate mates, find oviposition sites, escape predation or escape harsh environmental conditions (Chapman 1975). The majority of trivial flights occur without the insect leaving the habitat (Caprio and Grafius 1990, Voss

and Ferro 1990). Observed *A. lineatus* and *A. obscurus* flight seems to correspond to trivial movements flight behaviour to escape from environmental conditions presenting imminent risk of desiccation. Weather conditions prior to these observations had been overcast, cool and wet, well below seasonal normal, however, 12 May 2002 was the warmest day of the season to that date by several degrees. Sudden rising temperatures and drying of the soil in the field would have made the newly tilled field a less than ideal environment when combined with the first significant insolation event of the season. This putative escape behaviour has been observed in *A. obscurus* in Europe (Brian 1947) and in North America with the Colorado potato beetle which is also prone to desiccation from heat (Lactin and Halliday 1994, Boiteau *et al.* 2003).

The other type of flight is known as migration flight. These flights are described by Chapman (1975) as a dispersal mechanism which always involves females, but may or may not involve males and occurs usually over a very short period in most species of insects. These migration flights involve leaving the immediate habitat and either moving at low altitudes and having control of direction of movement or reaching higher altitudes where the direction of insect dispersal is dominated by the prevailing winds (Caprio and Grafius 1990). Both *A. lineatus* and *A. obscurus* click beetles were observed in relative mass flights on one occasion in both Surrey B.C. and Ladner B.C. on 12 May 2002, and again in fewer numbers on 24 May 2002 in Ladner (Crozier *et al.* 2003). The longest-range continuous flights observed were on 12 May in Ladner, where *A. lineatus* was observed in flight from a field under cultivation to a field of pasture travelling a distance of 108 m. These longer range flights are not likely evidence of migratory behaviour (i.e. for the purpose of egg laying or mate seeking), however, since they appeared to be

precipitated by the field disturbance and/or optimum conditions in the cultivated field for insolation. Although female *A. lineatus* were present, there were no confirmed female *A. obscurus* captured.

May (1976) describes insect flight as either occasional (perchers) or continuous (fliers). Perchers make only short flights and thermoregulate by adjusting their position to maximize or minimize insolation. Click beetles fall into the category of perchers. Other coleopterans, Japanese beetles, (*Popillia japonica*) have a maximum flight distance of 700 m in 5 hours (Hamilton and Gibb 2002) while Tiger beetles (*Cicindela hybrida*) achieve a flight speed of 3 m/s (Nachtigall 1996). Dung beetles have a minimum flight temperature of 25°C and a maximum of 42°C (Verdú et al. 2006) and their small body size allows them to keep their body temperatures close to ambient air temperature during flight. It is also suggested that differences in tolerated temperatures among species allow insects to niche partition thermally. These values are close to the range defined by May (1976) as the temperature of heat shock for insects, between 45°C and 47°C. The effects and temperatures, we observed in the study, are within the general parameters in these cited studies.

3.0 INDUCING *AGRIOTES LINEATUS* AND *A. OBSCURUS* (COLEOPTERA: ELATERIDAE) FLIGHT IN THE LABORATORY

3.1 Introduction

The dusky wireworm, *Agriotes obscurus* L., and the lined click beetle, *A. lineatus* L. (Coleoptera: Elateridae) are species of economic importance that have been introduced to British Columbia (Wilkinson 1963) and parts of the Maritimes (Eidt 1953) from Europe. Since their discovery in British Columbia in 1949 (King 1950; Lane 1952), both species have spread throughout the lower Fraser valley of BC and parts of Washington (Wilkinson 1963; Vernon and Päts 1997; Vernon *et al.* 2001). In recent years, these wireworms have become the most important agricultural insect pests of many vegetable, small fruit and ornamental crops in the Fraser Valley (Vernon *et al.* 2001).

With the decreased availability of traditional insecticides for wireworm control in Canada, more attention has been directed to developing alternative control methods and integrated strategies (Vernon *et al.* 2000). Pheromones have been identified for both species (Toth 1984), and traps have been developed for monitoring and surveys (Vernon *et al.* 2001).

Understanding the basic biology of a pest, makes it easier to develop better overall control strategies and focus limited research resources in areas that show the greatest promise of efficacy.

Flight is one aspect of life history that is critical to understanding pest behaviour. Both *A. lineatus* and *A. obscurus* adults have been observed to fly under field conditions when air temperatures exceeded 23°C under sunny skies. To determine whether flight activity in the field was in response to elevated air temperature, light intensity or a combination of the two, trials were conducted to separate the effects of temperature from light intensity on click beetle flight behaviour, with the benefit of being able to forecast conditions under which beetles are most likely to disperse.

3.2 Methods

Click beetle colonies: Male *A. lineatus* and *A. obscurus* beetles were captured from a 1 ha. field of pasture in Ladner, British Columbia using separate Vernon beetle traps containing synthetic female sex pheromone (Phero Tech® 7572 Progress Way Delta, British Columbia; lot# CB022201 and AOCB022201) baited with their respective pheromone (Toth 1984). Adult beetles were collected from the traps twice weekly throughout the adult life cycle of both species from 13 May to 22 June. Traps were partially buried in the ground (Vernon 2004) of the grassy headlands of potato fields consisting primarily of *Elytrigia repens*, where European click beetle populations of both species studied were known to exist. Beetles captured via pheromone traps were identified to species and were then held in one of two separate 45 cm (height) x 55 cm (width) x 75 cm (length) Plexiglas cages for each species. Two smaller 30 cm x 30 cm x 30cm Plexiglas cages held females collected from forage traps in addition to beetles identified as female within the pheromone traps having entered the traps by chance. Beetles fed upon wheat germinated in four 10 cm diameter pots placed inside each cage,

with the wheat reaching approximately 25cm in height. The total population of beetles alive at any given time varied due to mortality and subsequent twice-weekly pheromone trap catches added to the colony, but I estimate that the *A. lineatus* male colony was 300 living individuals at any given time while the *A. obscurus* male population was 60 living individuals. Seven female *A. lineatus* and four *A. obscurus* females were collected using forage traps, consisting of four handfuls of freshly cut grass of about 30 cm in length placed over a clear plastic sheet measuring 60 cm by 60 cm. Eight such traps were placed in freshly tilled fields in Ladner, British Columbia between 5 and 31 May 2001. A single female was found amongst the male *A. lineatus* beetles captured via female sex pheromone traps and relocated to the *A. lineatus* female cage. No females were found in a sample of the 30 *A. obscurus* beetles taken from the pheromone traps. Cages were kept outdoors to expose the beetles to ambient temperatures and photoperiod, and were brought into the lab to conduct the flight studies.

Flight studies: Prior to bringing cages into the lab, periodic outdoor observations were made on the movement of beetles within the cages at ambient air temperature ($\leq 17^{\circ}\text{C}$). These observations were usually made between 16:00 and 22:00 hours PST. The cages were brought into a lab measuring 1.6 m x 2.3 m x 2.4 m maintained at 22°C , and illuminated by two 20 watt overhead fluorescent lights. Studies took place on a lab bench. Insects were not reused except where noted in Table 1 due to insect availability constraints. Where insects were reused, a minimum 24 hour rest period was given.

My hypothesis was that ambient air temperature above the insect tolerance level initiated flight activity. The response variables were flight initiation at various temperatures, how long it took each species to reach flight initiation temperature and

beetle surface temperature in the case of infrared radiation. In order to determine if flight behaviour was in response to ambient air temperature, insolation, or light above the tolerance level of the insect, both *A. lineatus* and *A. obscurus* were subjected to an overhead infra-red light bulb, with and without the infra-red radiation using water as a filter, or heated air from a hairdryer under both lit and darkened conditions. Infrared radiation was provided by a 250 watt infrared heat lamp (Haskel Industrial) positioned 67cm directly above the Plexiglas cage. Heated air was provided by using a 1600 watt Conair™ (Rantoul, Illinois) hair dryer.

The *hair dryer* was aimed into a screen at the top of the cage so as not to directly contact the insects. This procedure was repeated in both daylight and dark conditions. Turning off the fluorescent light source and sealing the bottom of the door with a towel was sufficient to create dark conditions in the windowless lab. Observations were made under dark conditions by briefly turning on an overhead red filtered 100 watt flood light (Sylvania USA) 67 cm from the cage and by listening for the sounds of the beetle's wings while in flight activity.

Temperature within the cages at the initiation of each of the trials was usually about 17°C, as the cages were stored outside and timing started as the hair dryer or the heat lamp was switched on to measure the length of time needed to achieve flight. Temperatures continued to rise until a maximum temperature of 28°C was achieved. Air temperature was monitored inside the enclosure using a mercury bulb thermometer, and beetle surface temperature was recorded by aiming an automotive laser temperature gauge with an accuracy of $\pm 1.0^{\circ}\text{C}$ (Motomaster brand, Toronto, Ontario) directly at the thorax of the beetle for one second. In total, four trials were conducted using the infrared

light and four trials using the heated air from the hairdryer. The two blocking factors common to each treatment were species and sex of the beetles. In the heated air experiment, the blocking factor was light exposure with the two treatments being normal lab lighting (compact fluorescent) or darkness. Trials were conducted from 26 May to 6 July 2002 in Coquitlam, British Columbia. This time period coincided with the peak activity periods of both species in south-western BC in 2002 (R.S. Vernon, unpublished data).

To separate the effects of light from infrared radiation and determine if the light from the infrared lamp alone had an effect on flight activity, a clear glass container of water holding 4 litres of water was placed between the cage and the lamp to collect heat energy while allowing the light to pass through. Air and beetle temperature was taken as in previous trials.

3.3 Results

Beetle activity prior to turning on the heat lamp consisted of feeding and resting with very little movement. Under the heat lamp, flight activity occurred when the beetle surface temperature reached 26°C (*Table 1*) which corresponded to an air temperature of 23°C and a high relative humidity as condensation formed on the inside surface of the cage. Mean time to flight for *A. lineatus* was 157.66 seconds (n=68, SE=0.47) while *A. obscurus* achieved a mean time to flight of 147.33 seconds (n=64, SE=0.44). Once the heat lamp was turned off, flight activity became less frequent and stopped although the air temperature remained at 23°C.

No flight activity was observed in the cage of the heated air experiment prior to turning on the hairdryer. As air in the cage was heated from 17°C with the hair dryer, beetle flight activity for both species and both sexes, occurred between 54 and 66 seconds of turning on the hair dryer, which corresponded to a cage air temperature of 25°C (*Table 2*). This occurred in both daylight and dark conditions.

The glass and water heat barrier trial (*Table 1*) prevented the air in the enclosure from heating past 21°C and flight activity did not occur. It is also worth noting that flight activity occurred at all collected stages of the adult lifecycle from newly emerged to five weeks from time of collection, as well as having occurred in both sexes in both *A. lineatus* and *A. obscurus* in nearly 100% of the population when stimulated with sufficient heat.

Flight activity was artificially induced in captivity in nearly 100% of the sample population using heated air with beetles ranging in age from newly emerged (7 May 2002) to just before death in July, however, cage size constraints prevented accurate measurement of distance needed for flight speed calculations. However, this observation would seem to suggest that beetles are capable of flight throughout their adult life stage in addition to having occurred in both males and females of *A. lineatus* and *A. obscurus* when stimulated with sufficient heat.

Table 1 Initial and flight inducing surface and air temperatures for *A. lineatus* and *A. obscurus* of both sexes when exposed to infrared radiation from a heat lamp directly or with a water barrier in between, conducted under laboratory conditions in Plexiglas cages from 03 June to 06 July 2002 in Coquitlam, British Columbia. Note: 1) ^a indicates cage temperature at time of first flight; 2) ^b indicates flight did not occur within 5 minutes of observation; 3) ^c indicates individuals used from previous experiments due to low population numbers. All reused individuals received minimum 24 hours rest between experiments. 4) Beetle surface measurements were not available in July due to equipment availability.

Species	Sex	Date	Start temp (°C)	Beetle temp (± 1°C)	Cage temp (°C) ^a	Time to first flight (s)
<i>A. lineatus</i> (n=30)	M	03 June	17	26	23	180
<i>A. lineatus</i> (n=8)	F	06 June	17	26	23	158
Infrared absorbing water barrier						
<i>A. obscurus</i> (n=30)	M	03 June	17	26	23	166
<i>A. obscurus</i> (n=4)	F	06 June	17	26	23	149
<i>A. lineatus</i> (n=30)	M	05 July	21	-	23	135
<i>A. obscurus</i> (n=30)	M	05 July	21	-	23	127
Infrared absorbing water barrier						
<i>A. lineatus</i> (n=30)	M	06 July	20	-	21	No Flight ^b
<i>A. obscurus</i> (n=30) ^c	M	06 July	20	-	21	No Flight ^b

Table 2 Initial and flight associated temperatures for *A. lineatus* and *A. obscurus* of both sexes when exposed to heated air from a hair dryer under lighted and dark laboratory conditions from 26 May to 31 May 2002 in Coquitlam, British Columbia. Note: 1.) ^a indicates individuals used from previous experiments due to low population numbers. All reused individuals received minimum 24 hours rest between experiments.

Species	Sex	Date	Start Temp [°C]	Cage Temp at first flight [°C]	Mean Time to Flight in seconds (S.E.)
Light					
A. lineatus (n=30)	M	26 May	17	25	58 (0.5)
A. lineatus (n=5)	F	27 May	18	25	55 (0.8)
Dark					
A. lineatus (n=30)	M	26 May	17	25	57 (0.4)
A. lineatus (n=5) ^a	F	29 May	17	25	50 (0.4)
A. obscurus (n=20)	M	31 May	17	25	58 (0.6)
A. obscurus (n=5) ^a	F	31 May	17	25	66 (0.4)

3.4 Discussion

It is well known that body temperature is a major factor influencing ectotherms, strongly affecting behaviour, physiology and development (Precht *et al.* 1973).

Temperature is also considered the primary environmental stimulus responsible for inducing or regulating insect flight behaviour (Chapman 1975, Caprio and Grafius 1990, Naranjo 1991). Environmental temperature affects beetle flight behaviour in two ways; via ambient air temperature and from solar radiation being converted into heat energy, also known more commonly as insolation.(Caprio and Grafius 1990). Stevenson (1985) reports that the effects of insolation can elevate body temperature greatly above air temperature in terrestrial poikilotherms.

Increases in body temperature in several insect species accelerate physiological responses of nerve impulses that directly affect locomotion speed and duration (Termier *et al.* 1988). In general, insect response to temperature affecting flight behaviour have many similarities among species, in that most insects have a range of temperatures over which they can conduct flight activities and threshold temperatures above and below which flight is impossible (Chapman 1975). However, the exact threshold temperature for inducing activity varies greatly by species (Chapman 1975, Termier *et al.* 1988, Naranjo 1991). It appears that European click beetles require a body surface temperature of at least $26^{\circ}\text{C} \pm 1.0^{\circ}\text{C}$ to initiate a flight response. It is not known whether this is critical for the flight muscles of the European click beetles to achieve flight or whether the beetle is reluctant to use energy flying unless it faces the threat of desiccation. Both *A. lineatus* and *A. obscurus* seem prone to desiccation when exposed to direct sunlight and

temperatures in excess of 26°C and these temperatures occur during late spring and early summer in the Fraser valley of British Columbia (Environment Canada 2002).

However, the observation of flight at Ladner in 2002 on 24 May was observed at ambient air temperatures of 17°C. During this time period, although cloudy, the sun would break through the clouds periodically and the effects of insolation may have been sufficient to raise the surface temperature of the beetles to levels where flight was initiated. It is likely that sudden increases in body temperature could trigger a flight response in addition to the physical state (i.e. fitness) of the beetles at that point in time. Brian (1947) observed *A. obscurus* and *A. lineatus* flight in a greenhouse under bright, sunny conditions at temperatures of 21°C, yet in darkness, heated air temperatures of 23°C were insufficient to cause flight initiation. This is consistent with my findings because insolation could account for daylight flights in a greenhouse at 21°C, while the heated air in the absence of insolation (darkness) observation was still below the threshold calculated in my study.

The time to flight differences between species under insolation conditions might be explained due to relative colour or shape differences between *A. lineatus* and *A. obscurus*. The latter is a slightly darker shade of brown than *A. lineatus* and is slightly broader in the abdomen. As well, variations in reaching critical flight temperature may be explained by the various positions the beetles were in during exposure to the insolation. Stevenson (1985) describes a number of tactics and behaviours used by ectotherms to regulate body temperature and includes changes in elevation, body position relative to the sun (Stevenson 1985, Lactin and Haliday 1994), and even physiological factors such as integument design (Stevenson 1985). Other beetles for which flight

initiation temperatures are known include *Geotupes stercorarius* (35°C) (Krogh and Zeuthen 1941) and *Nicrophorus* sp. (20-38°C) (Merrick and Smith 2004).

On several occasions, click beetles in the field have been observed opening their elytra, spreading their wings and orienting into the wind, only to retract them and not fly (Crozier, personal observations). It may be that this behaviour has less to do with flight as it does in regulating the temperature of the insect. Often ectotherms will orient into the wind, climb to a higher elevation or move muscles to regulate body temperatures (Stevenson 1985). This behaviour may serve to change the amount of insolation on the elytra and cool the abdomen. Flight activity may be in response to temperature conditions exceeding the level by which orientation and fanning of wings can cool the insect. Experiments conducted by Lactin and Halliday (1994) have found Colorado potato beetle larvae do not seek out optimal conditions but accept ambient conditions until they become intolerable. Heath *et al.* (1971) also reports that a common strategy among insects is to abandon a site if conditions exceed tolerable parameters.

The fact that *A. lineatus* and *A. obscurus* are so similar in their response to environmental stimuli is not surprising because these species coexist in similar habitat and ranges throughout Europe and Asia, and have very close chemical pheromone components when compared with other similar species (Kudryavtsev *et al.* 1993). It appears that although these species overlap in distribution closely, *A. lineatus* prefers coastal sites as opposed to *A. obscurus* which typically inhabits upland soils with higher pH.

Two factors not accounted for in my study were the potential lag time between insect body temperature and observed flight response. The apparatus used in this

experiment was not capable of holding a specific temperature for a prolonged period of time, stepwise temperature observations would have enabled more precise measurement of latency between insect behaviour thresholds and observed behaviour. In addition, the effect of excessive volume of noise generated by the hairdryer was not accounted for in this experiment as a control. Although it is possible that the noise level contributed to flight initiation, I observed no flight activity in non treated cages 3 meters away when the apparatus was in use.

Discrepancy between the air temperature for which flight is achieved with the hair dryer and the heat lamp seems logical in that the actual temperature of the ectothermic insect is only affected by the air temperature in the case of the hair dryer. However, in the case of the infrared heat lamp, both air temperature and infrared radiation act to heat the beetle to its critical flight temperature before the air temperature reaches this threshold on its own. It is also possible that the temperature threshold acts as a bio-indicator to trigger a flight response when local environmental conditions are optimal for mate selection, egg laying or density dependent dispersal. Termier *et al.* (1988) showed that rapid increases in light intensity causes Colorado potato beetle to initiate flight activity and that flight activity may not occur even under suitable temperatures if insolation is blocked. In what would seem to contrast my study, Brian (1947) found that *A. lineatus* and *A. obscurus* would not fly in dry air and that relative humidity in excess of 80% and sunlight was needed. Although relative humidity was not quantified in my study, flight was initiated through heated air from a hair dryer in both darkness and artificial light conditions at temperatures in excess of 25°C, which were above the experimental temperatures used by Brian (1947).

Flight behaviour has been observed in the Colorado potato beetle, which appears to have similar temperature thresholds to European click beetles, below known threshold temperatures when preceded by long periods of insolation (Caprio and Grafius 1990, Boiteau *et al.* 2003). This may explain click beetle flights observed on 24 May 2002 in Ladner, BC where the air temperature of 17°C was well below the experimentally derived ambient air critical flight initiation temperature of 25°C, but microclimate conditions may have permitted sufficient insolation to raise the internal temperature of the beetles above the threshold temperature. Chapman (1975) writes that in addition to insolation, beetle internal temperature may be greatly increased by muscle activity.

Another important observation is that both species studied were capable of achieving directed flight under wind conditions in the field of at least 13 km per hour, and under laboratory conditions where the hair dryer was used to raise the air temperature creating a significant amount of air current. Chapman (1975) considers directed flight in wind speeds above 10 km per hour to represent a strong flyer and Brian (1947) notes that *A. obscurus* is a stronger flier than *A. lineatus*.

4.0 POTENTIAL FLIGHT DAYS AT THREE LOCATIONS IN THE LOWER MAINLAND OF BRITISH COLUMBIA FROM 1997-2002

4.1 Introduction

Having accumulated evidence for a threshold temperature of 25°C, at or above which *A. lineatus* and *A. obscurus* are capable of flight; this information could be used to determine the frequency of occurrence of temperatures above the putative flight-initiating threshold across the Lower Fraser valley of BC. Comparing the occurrence of click beetles in the wild with corresponding local historical temperatures along the Fraser valley, it would be possible to calculate the average number of days expected above the threshold temperature for each location. Through comparisons of the proportion of beetles emerging in a given month to the average number of days equal to or exceeding the critical flight temperature, a better understanding of the potential frequency of flight behaviour in these species can be predicted and help to predict flight opportunity frequency in other locations.

4.2 Methods

Weather data (Environment Canada 2006) were analysed at three locations along the lower Fraser valley to determine the number of days at which ambient air temperature alone would induce flight by *A. lineatus* and *A. obscurus* click beetles. Three selected locations at Richmond, Langley and Agassiz represent the mouth (west), mid-point and head (east) of the valley, respectively, and also a gradient of temperature extremes

increasing from west to east. These weather stations are close in proximity to three click beetle pheromone trapping studies where beetle captures were monitored between 2001 and 2004. The number of days where the temperature exceeded 25°C for each of the three locations was determined from Environment Canada data between the period of April 1997 and July 2003. Mean values for these locations were calculated from data between the thirty year period 1970 and 2000.

To determine a range of adult beetle activity for both species, pheromone trap catch data from Agassiz, Cloverdale and Westham Island, British Columbia were analyzed to approximate the limits of adult emergence and death at these three locations. Vernon beetle traps® (PheroTech) were used according to the procedure outlined in Vernon (2004), and consisted of a pair of traps each with a species specific sex pheromone corresponding to either *A. lineatus* or *A. obscurus*.

From these data, a percent of the total beetle population trapped by month was calculated and compared with the corresponding monthly mean number of days $\geq 25^{\circ}\text{C}$ at each location. Because pheromone trapping lures male *A. lineatus* and *A. obscurus* throughout their adult lifespan, it serves as the best available approximation of population activity over time.

4.3 Results

The following data for mean temperatures for the three locations is presented in Figure 1; while percent sample population numbers by month and the average number of days $\geq 25^{\circ}\text{C}$ are presented in Table 3.

Agassiz: At the furthest inland site, *A. obscurus* was the predominant species accounting for 99.1% of all captures. Temperature data for this location are on site from the

Agriculture and Agri-food Canada research station (49° 14' N, 121° 45' W). By the end of April, 9.6% of the population of *A. obscurus* was exposed to, on average, 0.5 days at or above 25°C between 2001-2004. The mean daily maximum temperature for April was 14.7°C. By the end of May, 78.8% of the adult population had emerged to date and those emerging during May had been exposed to, on average, 3.0 days of ambient air temperatures $\geq 25^\circ\text{C}$, with a mean daily maximum temperature of 18.1°C. By the end of June, the remaining *A. obscurus* population to date had been exposed to a mean of 10 days where the air temperature was $\geq 25^\circ\text{C}$. The mean daily maximum temperature for June was 20.5°C.

Cloverdale: At this site near the centre of the Fraser valley (49°05'37"N, 122°44'57"W), *A. obscurus* accounted for 39.9% of the total sample population while *A. lineatus* comprised 60.1%. The mean daily maximum temperature was 14.8°C for nearby Langley, British Columbia (5.4 km east of the field site in Cloverdale, 49° 3' N, 122° 34' W) for the month of April, and corresponded to 19.5% of the total sample population of *A. lineatus* and 32.5% of *A. obscurus*. During this month, a mean of 0.43 days were $\geq 25^\circ\text{C}$. For May, 75.7% of the total sample population of *A. lineatus* and 90.3% of *A. obscurus* had emerged and were exposed during that month to a mean of 1.43 days $\geq 25^\circ\text{C}$. The mean daily maximum temperature for May was 17.6°C. By the end of June, 92.4% of *A. lineatus* and 98.6% of the *A. obscurus* sample population had been exposed to a mean of 5.14 days $\geq 25^\circ\text{C}$ in that month. The mean daily maximum temperature for June between 2001-2004 in Langley was 20.8°C.

July is traditionally the end of the beetle emergence period in B.C., thus, near 100% of the total sample population of both species had emerged and was exposed to a mean of 12.83 days $\geq 25^{\circ}\text{C}$ during the month. The mean daily maximum temperature for July was 23.7°C

Westham Island: This site is an island in the delta of the Fraser River ($49^{\circ}05'14''\text{N}$, $123^{\circ}09'36''\text{W}$) located at the western-most fringe of the City of Delta, BC.

Weather data were taken from Richmond, BC, 9.1 km northeast of Westham Island. In the month of April, 6.3% of the total sample population of *A. lineatus* and 6.6% of *A. obscurus* had emerged. For the period from 2001-2004 for Westham Island, the mean number of days $\geq 25^{\circ}\text{C}$ was zero. The mean daily maximum temperature for April was 15.1°C . For May, 49.3% of the total sample population of *A. lineatus* and 61.7% of *A. obscurus* had emerged and were exposed to a mean of 1.17 days $\geq 25^{\circ}\text{C}$. The mean daily maximum temperature for May was 18.4°C . By the end of June, 81.6% of *A. lineatus* and 88.0% of the *A. obscurus* sample population had emerged and been exposed to 5.0 days $\geq 25^{\circ}\text{C}$ during this month. June's mean daily maximum temperature was 21.1°C in Richmond. For July, 98.1% of the total sample population of *A. lineatus* and 99.5% of *A. obscurus* had emerged and were exposed to a mean of 13.83 days $\geq 25^{\circ}\text{C}$ in that month. The mean daily maximum temperature for July was 23.7°C . Variation in monthly temperatures between locations was compared using SAS (1999) GLM procedure and Tukey's Studentized Range Test. There were no significant differences in number of days equal to or exceeding 25°C between the three locations at the $\alpha=5\%$ level, nor were there significant differences between percentage of beetles trapped by month at the three locations .

Table 3 Proportion of the total monthly number of two species of click beetles (*Agriotes obscurus* and *A. lineatus*) in pheromone traps, and the mean number of days in that month where the temperature reached the critical flight threshold of 25°C at three locations in the Fraser valley of BC between the years 2001 to 2004. Note: 1) Values for *A. lineatus* are shaded. 2) Pooled mean represents the cumulative average total percent of the beetle population trapped for both species by month. 3) Mean YTD % of population refers to the average year to date percentage of both *A. lineatus* and *A. obscurus* for the indicated month.

Location	April		May		June		July	
	% trapped /year	# days $\geq 25^{\circ}\text{C}$	% trapped /year	# days $\geq 25^{\circ}\text{C}$	% trapped /year	# days $\geq 25^{\circ}\text{C}$	% trapped /year	# days $\geq 25^{\circ}\text{C}$
<i>A obscurus</i>								
<i>A lineatus</i>								
Westham	6.64	0	61.74	1.17	88.07	5	99.46	13.83
	6.31		49.32		81.59		98.12	
Cloverdale	32.47	0.43	90.34	1.43	98.65	5.14	100	12
	19.54		75.70		92.36		100	
Agassiz	9.58	0.5	78.77	3	100	6.5	100	12.83
	0		0		100		100	
pooled mean								
Mean ytd % of population	12.42	0.31	59.31	1.87	93.45	5.55	99.6	12.89

4.4 Discussion

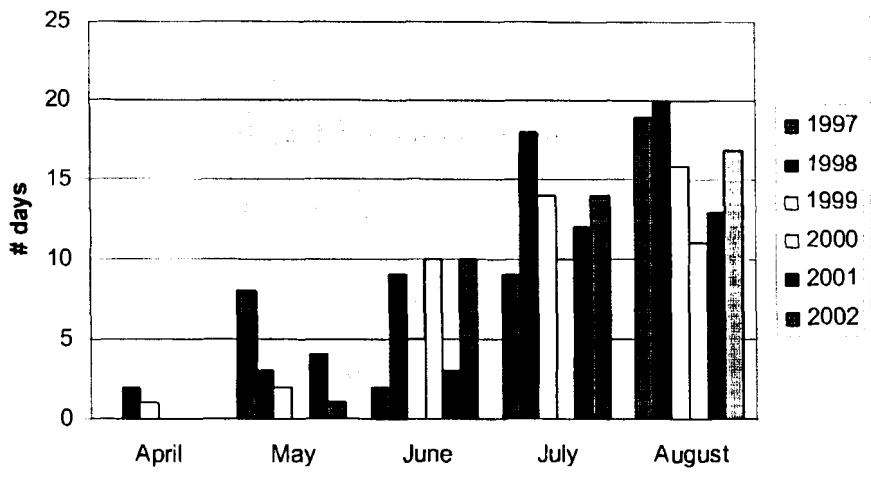
Agriotes ustulatus Schaller is a widespread European wireworm species found in Western Europe which borders both native *A. lineatus* and *A. obscurus* distributions (Kudryavtsev *et al.* 1993, Furlan 1996). According to Furlan (1996), *A. ustulatus* populations in Italy oviposit 5 to 7 days after adult emergence, and the oviposition period lasts 2 to 4 days. A 1:1 sex ratio was also reported (Furlan 1996). This would suggest that the vast majority of oviposition would occur two weeks after adult emergence, and oviposition activity would be expected to closely follow adult emergence trends by approximately two weeks. After oviposition, flight activity by the adults is of much less importance in terms of population management, as the adults themselves do little damage to crop plants. As Vernon *et al.* (2001) have demonstrated, chemical pheromone trapping efficiency is high throughout the adult life of *A. lineatus* and *A. obscurus*. This high efficiency could then serve as an approximation of a relative population sample for males in the species. If the sex ratio is assumed to be 1:1, it would then be reasonable to expect that trap catch data would closely approximate adult emergence and also oviposition trends with a lag time of about two weeks.

Between the three trapping locations, there were no significant differences in the percentages of beetles caught for each month nor were there significant differences in the number of days $\geq 25^{\circ}\text{C}$. April has approximately 12% of the total population of the two *Agriotes* species and averages only 1 day in three years which exceeds the estimated ambient air temperature threshold (EAAT) (Table 3). Of this 12%, the vast majority would be expected to be ovipositing. By the month of May, approximately 60% of the

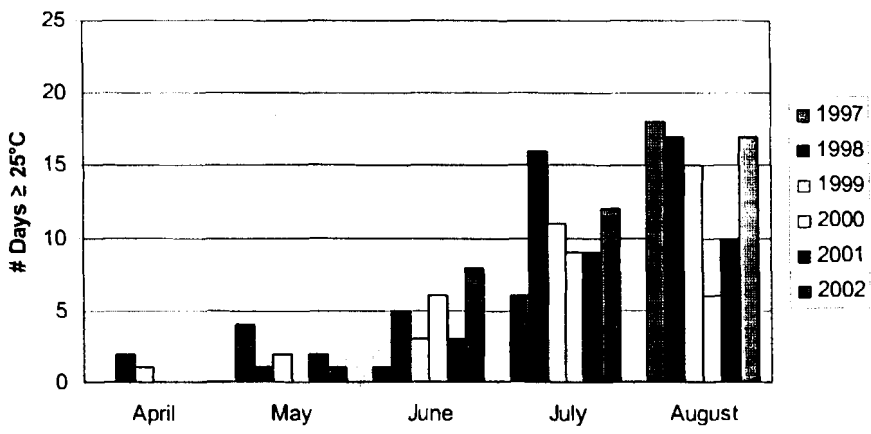
total population had emerged with approximately 47% of these emerging in May alone and were exposed to an average of 1.87 days above the EAAT. By June, 93% of the total population had emerged and ~34% within the month of June, and were exposed to an average of 5.5 days above the EAAT. July accounts for ~6% of the total population (99.60% ytd) and were exposed to an average of ~13 days above the EAAT. In terms of wireworm population management, temperatures exceeding the EAAT during June and July are most critical, as these affect an average of 81% of the total adult population for these two species. While July does receive a higher number of days above the flight threshold temperature (Figure 1), it represents only a small fraction of the total population (Figures 2 and 3). While there is little that can be done to mitigate these temperatures, practices such as tilling during these types of temperatures may in fact lead to greater numbers of wireworm flights. The impact of increased flights from tilled fields might include increased mating and egg laying in the grassy headlands surrounding the fields, which could be targeted for mass trapping or pheromone disruption control strategies. With 93% of beetle emergence and ovipositing occurring from April to June, corresponding to an average of 7.73 days where the temperature exceeded the EAAT, it is not surprising that beetle flight activity has not been observed with a higher frequency. Variations in climatic trends from year to year may also account for the lack of flight observations during periods of short term monitoring. While the relative number of flight opportunities available due to temperature exceeding the flight threshold are low for climates such as the Fraser valley, warmer climates may in fact see increased flight activity in these species. However, ambient air temperature alone does not account for all flight activity. Beetles which are sufficiently insulated by the sun may in fact increase

their body temperature to temperatures above ambient. This has been previously demonstrated in Coleopterans such as *Leptinotarsa decilineata* (Lactin and Halliday 1994), *Diabrotica virgifera vergifera* (Isard *et al.* 2004) *Anthonomus pomorum* (Hausmann *et al.* 2005) and Dipterans like *Tabanus nigrovittatus* and *T. conterminus* (Gaugler and Shultz 1989) and the sub arctic species *Hybomitra arpadi* (Smith *et al.* 1994) which has been found to achieve a thoracic temperature 23.5°C above ambient air temperatures from insolation

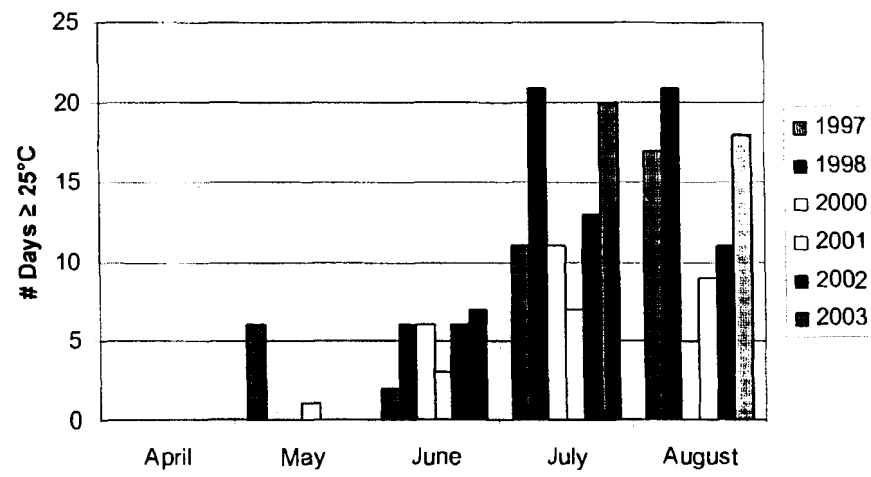
Figure 1 Number of days in Agassiz ($49^{\circ}14'N$, $121^{\circ}45'W$), Langley ($49^{\circ}3'N$, $122^{\circ}34'W$), and Richmond ($49^{\circ} 10' N$, $123^{\circ}5'W$) respectively. British Columbia, equal to or exceeding a temperature of $25^{\circ}C$ per month from 1997 to 2002.



Agassiz

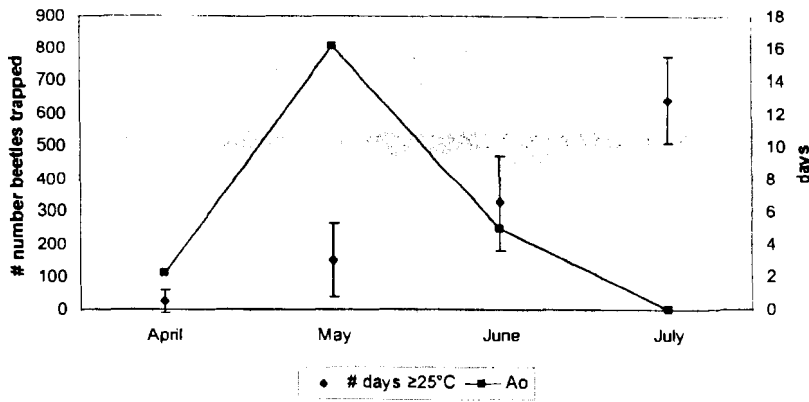


Langley

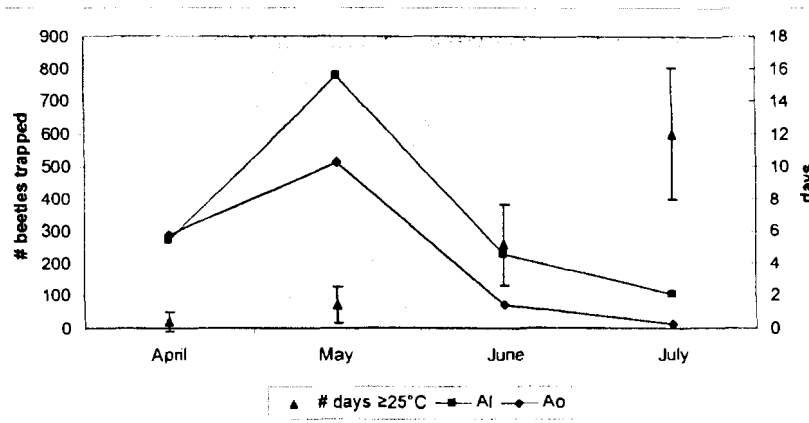


Richmond

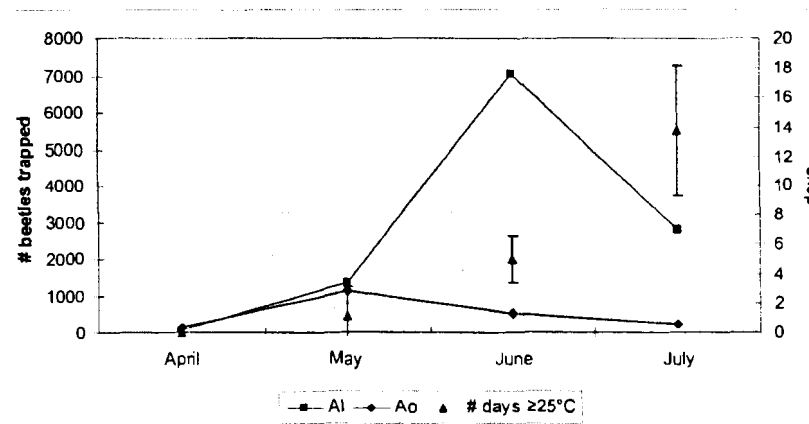
Figure 2 Total *Agriotes obscurus* beetle captures per month using the Vernon pheromone trap in 2001 at Agassiz, BC (49°14'N, 121°45'W), Langley (49°3'N, 122°34'W), and Richmond (49° 10' N, 123°5'W) respectively. Note: 1.) While both beetle species were captured in Agassiz, *A. lineatus* populations were proportionally smaller (n=11) and trapped in a single month, therefore is not presented due to the scale of the Y1 axis (left). 2.) The average number of days where the mean daily maximum temperature was $\geq 25^{\circ}\text{C}$ at Agassiz is plotted [# days] on the Y2 axis (right).



Agassiz

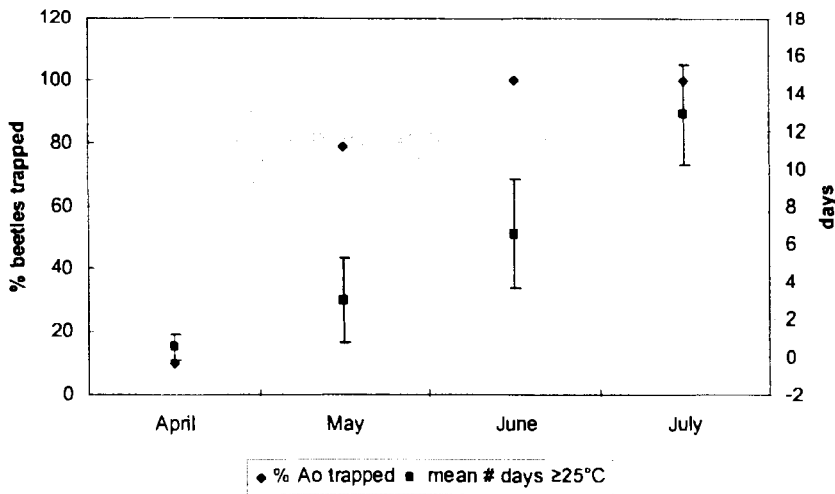


Langley

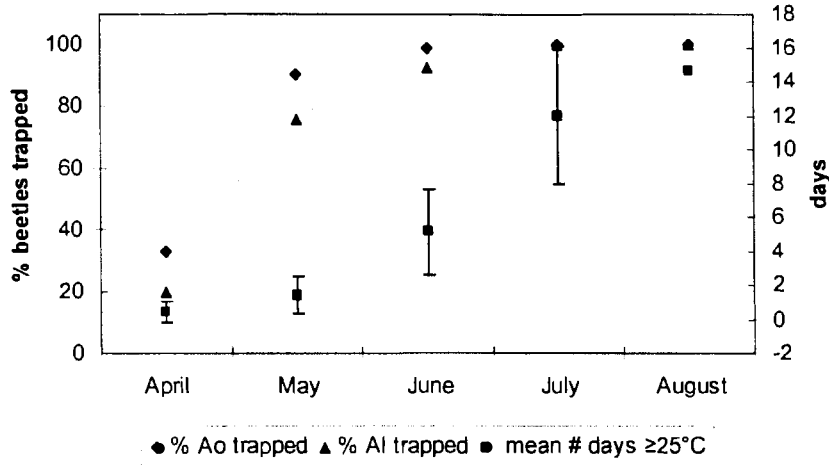


Richmond

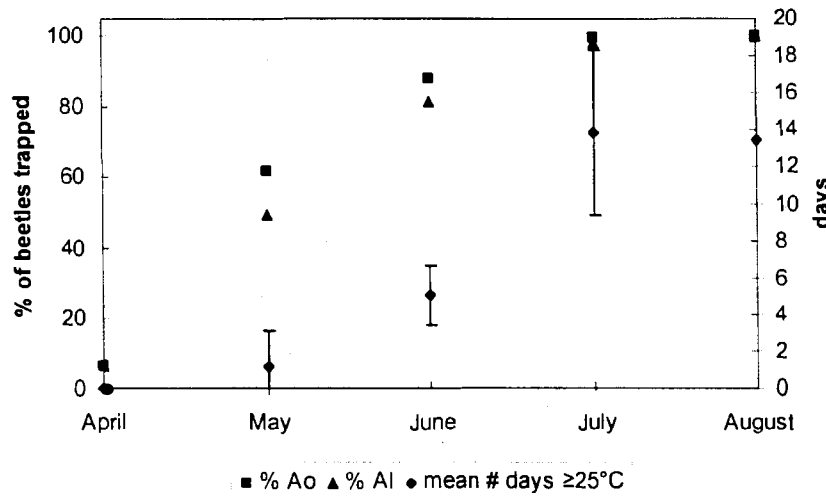
Figure 3 Percentage of total *Agriotes obscurus* beetles captured in Vernon pheromone traps during 2001 at Agassiz (49°14'N, 121°45'W), Langley (49°3'N, 122°34'W), and Richmond (49° 10' N, 123°5'W) British Columbia respectively on the Y1 axis (left) and the average number of days $\geq 25^{\circ}\text{C}$ from 1997 and 2002 for the same location on the Y2 axis (right). Note: While both *A. lineatus* and *A. obscurus* were captured in Agassiz, *A. lineatus* populations were proportionally smaller (n=11) and trapped in a single month, therefore data are not presented.



Agassiz



Langley



Richmond

5.0 DISCUSSION

5.1 Consequences of Temperature Regulated Flight Control

While uncommonly observed in the field, flight activity can and does occur in both *A. lineatus* and *A. obscurus* when environmental conditions are at or above a threshold of tolerance. This is not surprising, because several species of elaterids are known fliers (Cherry and Hall, 1986) and even within the genus *Agriotes*, there are well known instances of flight activity in Europe (Brian 1947, Furlan 1996). In England, Brian (1947) attributed the scarcity of flight observations in *A. obscurus* to the low temperatures associated with the climate. Furlan (1996) records trivial and swarming flights for *A. ustulatus* in Italy during the warmest periods of the day corresponding to 15:00h and that no night activity occurred. This is consistent with my observations on *A. lineatus* and *A. obscurus*, although not all elaterids are restricted to diurnal flight. Cherry and Hall (1986) report flight at night for the common wireworm species *Melanotus communis*, while Brian (1947) reports *A. sputator* flight at dusk. The original report of *Agriotes* flight in England by Fryer in 1941, however, is inconsistent with my findings because his specimen was captured at night using a lantern and drop cloth. Identification of this specimen as *A. obscurus* is unlikely but not impossible for several reasons: 1) Light trap surveys for *A. lineatus* or *A. obscurus* in Ladner, BC (known to have populations of both species) were unsuccessful in attracting either species (unpublished data); 2) The temperature needed for flight by ambient air alone after sunset would have to be high; and 3) Neither *A. lineatus* nor *A. obscurus* from my work, or *A. ustulatus* in

Europe are known to have flight activity at night (Furlan 1996). It is more likely that the species observed by Fryer was confused with *A. sputator* which is known to coincide with *A. lineatus*/*A. obscurus* populations on the southern range of these species (Kudryavtsev 1993). As well, *A. sputator* exhibits flight behaviour at dusk (Brian 1947) and is similar in appearance to *A. obscurus*.

The observed flight potential of the adult European wireworm would diminish the efficacy of physical exclusion devices that had been developed to prevent click beetles from entering fields by walking (R. Vernon, personal communication). Studies have also demonstrated that in addition to air temperature, humidity also plays an important role in thermoregulation of insects (Krogh and Zeuthen 1941, Haufe 1966). Dry air was found to decrease the temperature of an insect's body through evapotranspiration, while saturated air insulated the body temperature of the insect. It was also noted that nearly all insects will, in a gradient, choose a humid environment if desiccated, and a dry environment if saturated (Haufe 1966). Thus it is feasible that humidity may either prohibit or induce the flight of *A. lineatus* and *A. obscurus* click beetles at an ambient air temperature at or above 25°C, depending on the saturation state of the beetle. This may have consequences for differences in dispersal and spread at locations with higher humidity such as Delta and Ladner, BC, or the Maritime provinces *versus* dryer inland locations like Agassiz BC. According to May (1979) the state of the insect in terms of its level of hydration may have a greater influence, as humidity may have little effect on a well hydrated insect yet a desiccated insect will seek lower temperatures even in high humidity. Additional research is needed to investigate the role of relative humidity and the level of insect saturation as a barrier or motivator of flight behaviour.

Josephson *et al.* (2000) found that beetle flight muscles operate at defined temperature ranges with an optimum temperature whereby maximum work can be done by the muscles. To achieve this temperature, insect muscles must receive sufficient heat energy in the form of solar insolation (Halliday and Lactin 1994) through convection from surrounding air (May 1976), or internal friction from the use of the muscles (Heath *et al.* 1971). In the case of click beetles, observed behaviour in the field when temperatures exceeding the flight threshold may actually represent a threshold of temperature tolerance, whereby the insect chooses to remain in a location until conditions exceed a tolerable level as proposed by Heath *et al.* (1971) and confirmed by Lactin and Halliday (1994). Having reached this threshold level of tolerance, the insect would then try to escape these conditions for more favourable environments. This was demonstrated by Lactin and Halliday (1994) where Colorado potato beetle larvae sought shelter when ambient air temperature and insolation increased beyond tolerable levels. They found that insolation, measured in units of watts per m², had the same effect on beetle avoidance behaviour as ambient air temperature. Their measurements found that 1 watt per m² had an equivalent behavioural effect on the beetles as an increase of 0.08°C in ambient air temperature. To raise the temperature 1°C, 11.93 watts would be required. Extreme values for insolation, recorded at Race Rocks, BC in 2006, the closest available insolation data, situated at the eastern entrance of the Strait of Juan de Fuca on Vancouver Island had a maximum of 874 watts/ m² for April, 1174 watts/ m² for May, 1192 watts/ m² for June and 1218 watts/ m² for July (Fletcher 2006). While these values are extremes, they demonstrate the potential for theoretically elevating a beetle's surface temperature by as much as 100°C if the insect is directly exposed for sufficient duration

according to the model developed by Lactin and Halliday (1994). On average, low latitudes typically receive 400W/m^2 at noon on a clear day (Stevenson 1985) which is the equivalent behavioural temperature of 33.5°C in air. In combination, temperature and insolation at high levels would also be expected to contribute towards the desiccation of beetles that were exposed for prolonged periods of time to these conditions, or for those individuals unable to obtain shelter. Other environmental factors that enhance insolation include slope aspect and vegetation cover. A south sloping field would be expected to receive higher insolation, while vegetation type and percent canopy cover would similarly affect the amount of insolation received.

Traditionally, insolation of field crops using polyethylene plastic sheets has been used in agriculture to control weed infestations by destroying weed seed banks (Arora and Yaduraju 1998) and to sterilize soils to control populations of nematodes and fungi (Katan 1981). While this may seem an attractive potential option for wireworm control, most effective solarisation programs occur in tropical to subtropical locations where the effects of soil insolation can reach to depths of 10 cm or more as well, disposal of plastic ground covers has become a significant labour and environmental cost. In a temperate climate, such as the Fraser valley, prolonged periods of solarisation would be required to reach depths required to kill wireworms or click beetles, but similar effects could be achieved by summer fallowing at a fraction of the cost. In addition, the effects of solarisation would not prevent immigration back into a field the next year by adults from adjacent refuge areas.

Ambient air temperatures alone are not responsible for the elevation of body temperatures to levels exceeding the temperature for which flight is possible for *A. lineatus* and *A. obscurus* and that insolation could have the greatest impact when temperatures are just under the EAAT, triggering the beetles to fly at lower ambient air temperatures, such as the observed flight activity on 24 May 2002 where the click beetles were capable of short flights at an ambient air temperature of 17°C

It is entirely likely that flight activity occurs outside of the estimated thresholds that were measured in the lab. Ambient air temperatures were measured throughout this study as a substitute for body surface temperatures, however, it has been noted earlier that insect body surface temperatures have been known to easily exceed ambient air temperatures due to conditions of insolation or other mechanisms of radiant heat transfer from the surrounding environment. The potential for flight occurring at lower threshold temperatures could be in response to individual beetle fitness and therefore intolerance to higher temperatures (risk of desiccation) or conversely, flight at higher thresholds may suggest greater fitness or tolerance to desiccation. The experimentally derived estimates of flight threshold were conducted on sub populations of beetles which were held in captivity and presented with the same food opportunities and ambient temperature. It is possible that insects held at different ambient temperatures or those who have different levels of hydration may undertake flight at lower temperature thresholds. The impacts of potential fitness variation on the flight initiation temperature need further investigation

5.2 Direction for further study

Little attention has been given to the adult biology of wireworm species; in particular distribution and behaviour of these adults under field conditions (Furlan 1996,

Parker and Howard 2001). The role of humidity needs to be investigated in relation to temperature to develop a hygrothermal model of water balance such as that developed by Haufe (1966) for *Aedes aegypti*. Both temperature and humidity have been shown to affect biochemical reactions and physiological processes in insects in terms of enzyme activity, wing beat frequency, pheromone production and response thus creating numerous variables for movement and distribution (May 1979, Oertli 1989, Horn 1998). The role of optic cues has been shown in Colorado potato beetle to influence such activities as flight initiation, migration orientation and trap avoidance (Noronha and Cloutier 1999, Boiteau *et al.* 2003, Boiteau 2005). Colorado potato beetles actively orient towards large objects which simulate forest boundaries which serve as over wintering sites. This information is critical to management of pest species like the Colorado potato beetle and European wireworms because it provides insight into predicting their behaviour. If behaviour is predictable, their exploitation based on this predictability becomes increasingly reliable (Foster and Harris 1977). Better definition of the conditions under which the European click beetles are likely to achieve flight activity will help in understanding how the insect interacts within its environment, ultimately leading to integrated pest management tactics that can exploit these interactions.

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