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Julie Stachecki Johanningsmeier

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RELATIONSHIP OF *APHODIUS GRANARIUS* AND *ATAENIUS SPRETULUS* ACTIVITY TO AIR AND SOIL BASED DEGREE-DAY ACCUMULATIONS ON MICHIGAN GOLF COURSES

By

Julie Stachecki Johanningsmeier

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ABSTRACT

Relationship of *Aphodius granarius* and *Ataenius spretulus* Activity to Air and Soil Based Degree-Day Accumulations on Michigan Golf Courses

By

Julie Stachecki Johanningsmeier

In Michigan, *Ataenius spretulus* larval feeding has damaged golf course turfgrass and its presence has become more common and injury more prominent. Further, initial sampling revealed that *Aphodius granarius*, another Scarabaeidae beetle, was also present and causing injury on golf course turfgrass in Michigan. The biology of these pests in the state of Michigan has not been thoroughly understood. Therefore six golf courses were sampled from April through September for *A. spretulus* and *A. granarius* life stages. Air and soil temperature data were sampled at three of the golf course sites, at 0.3 m above, and 2.0 cm and 5.0 cm below irrigated turfgrass, respectively and were converted to degree-days (DD) base 10°C beginning April 5 of the respective year. Life stages of the beetles were compared to the golf course air and soil DD accumulations and two sets of weather data from local National Weather Service stations.

A. granarius and *A. spretulus* life cycles were not well correlated with any of the DD indexes during these two years. Peak *A. granarius* larval activity occurred prior to that of *A. spretulus* between calendar dates 174 and 181 in 1992, and between 165 and 172 in 1993. Calendar dates were a more accurate predictor of peak *A. spretulus* grub activity than DD. In 1992 (leap year), peak *A. spretulus* occurred between calendar days 202-209, and 200-207 in 1993. During these two years of observations, *A. granarius* and *A. spretulus* were univoltine in Michigan.

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INTRODUCTION

Ataenius spretulus (Haldeman) has been found in 41 of the United States and is known to have caused damage to golf course turfgrass in at least 23 states (Tashiro, 1987). In Michigan, *A. spretulus* larval feeding has damaged golf course tees, greens and fairways and its presence is becoming more common and injury more prominent. While this Scarabaeidae beetle's occurrence is familiar, limited information has been available on the biology of *A. spretulus* in Michigan.

The root-feeding larvae of *A. spretulus* have caused injury or death of many host turfgrasses including *Poa annua* L., *Poa pratensis* L., and *Agrostis* species (Tashiro, 1987). In West Virginia and Southern Ohio, *A. spretulus* completes two generations per year (Wegner and Niemczyk, 1981; Weaver and Hacker, 1978). In western New York, Ontario, Canada, and Minnesota, *A. spretulus* is believed to have one generation per year, although this is not confirmed (Tashiro, 1987).

In addition to *A. spretulus, Aphodius granarius* (L.) have been found causing turfgrass injury on golf courses in Michigan. The first description of damage to turfgrass by *A. granarius* was from a golf course in Toronto, Ontario in 1976 and 1977 (Sears, 1978). Populations of *A. granarius* on golf courses have been observed in Michigan and elsewhere, as homogenous and more often mixed with *A. spretulus* (Tashiro, 1987). The adults are shiny black beetles about 5 mm long and easily mistaken for *A. spretulus* (Tashiro, 1987). The white, c-shaped larvae cause injury by feeding on turf roots.

Sampling for *A. spretulus* or *A. granarius* larvae in turfgrass is a precarious task for golf course superintendents. Often, by the time turf damage from larval feeding is apparent, the immatures have begun to pupate. Understanding the timing of their life stages will help determine when to sample for larvae of these two species and when the best opportunity for control exists. This study resulted from the need to learn the life cycles of *A. granarius* and *A. spretulus* on Michigan golf courses.

A method used among scientists and agricultural producers interested in the biological development of many plants and cold-blooded animals is a temperature-derived index, growing degree-days, or simply degree-days (DD). Degree-days are based on the fact that growth and development of many plants and insects are dependent upon the amount of heat present in and or around the organism, and are normally used to estimate the amount of time spent above some organism-specific temperature threshold (Andresen, 1993). Part of this study was designed to relate *A. spretulus* and *A. granarius* life stages to DD. The hypothesis is that DD will be helpful in predicting their life stages, the larval stage in particular, in Michigan.

Since *A. spretulus* and *A. granarius* spend the winter in the soil and organic debris, and the egg, larval and pupae stages occur completely in the soil, it seemed logical to monitor accumulating thermal units in the soil. This study monitored DD for air temperatures and soil temperatures at 2.5 cm and 5.0 cm depths to determine which is a better indicator of the insects' development. In addition, two regional weather observation station DD indexes were compared to on-site golf course temperature data and the *A. spretulus* and *A. granarius* biological activities. Using air and soil temperature data should allow weather-related information to be a resource, enabling turf managers to interpret biological events so they may be more efficient at monitoring and managing turfgrass and its pests.

LITERATURE REVIEW

Aphodius granarius

Aphodius granarius (L.) is in the order Coleoptera, family Scarabaeidae, and subfamily Aphodiinae. The Scarabaeidae family is one of the most diverse in the order based on biology, ecology and behavior (Woodruff, 1973). The family is divided into two groups based on morphology. The Laparosticti group has abdominal spiracles situated in a line on the membrane between the sternites and tergites. This group includes the dung-feeding and scavenger species of which Aphodiinae are a part (Woodruff, 1973). There is limited reference material on *Aphodius granarius* and much of what is available on the genus is in reference to dung habitat and dung-feeding behavior (Borror et al., 1989; Ritcher, 1966; Wilson, 1932; Woodruff, 1973).

A. granarius is an introduced species which is now widespread in the United States and Canada (Ritcher, 1966). Adults are oblong, shiny black beetles approximately 3-5 mm long with reddish-brown legs and paler antennae. The adults resemble *Ataenius spretulus* and are often mistaken as such (Tashiro, 1987). The adult *A. granarius* is distinguishable by the transverse carinae on the tibia of the meso- and metathoracic legs. Woodruff (1973) states that adults of many species of *Aphodius* have been found on snow in the winter and that some species fly in swarms when emerging from overwintering sites during early spring in northern latitudes.

A research team in Sapporo, Japan studied the oviposition habits of Aphodiinae with hopes of revealing information useful in studying the evolutionary origin of two major groups of dung beetles: Geotrupinae and Scarabaeinae (Yoshida and Katakura, 1992). From the nine species of *Aphodius* that they studied, four types of oviposition habits were recognized. Type I: Eggs were laid singly in dung on the ground. Type II: Eggs were laid singly in soil beneath the dung. Type III: Each egg was laid in a small dung mass that had been stuffed in a shallow burrow excavated beneath the dung. Type IV: Each egg was laid in the soil near the terminal end of a sausage-shaped dung mass buried beneath the dung (Yoshida and Katakura, 1992). Adult *A. granarius* have been found abundantly in cow and sheep dung (Ritcher, 1966; Wilson, 1932; Woodruff, 1973). Wilson observed that the adult *A. granarius* preferred dung piles that had dried out and formed a hard crust on the surface. It was under this hard crust that they laid their eggs. *A. granarius* adults and larvae are also found inhabiting soils under golf course turfgrass indicating that oviposition occurs in turfgrass soil as well as in dung.

The oval-shaped *A. granarius* eggs are smooth, opaque and are approximately 0.80 mm long by 0.56 mm wide (Wilson, 1932). Wilson observed that eggs hatched in four to seven days and the first instar lasted three to four days (1932). In a microcosm study, the development of *A. fimetarius* agreed with the general life cycle of aphodiinae beetles in the field (Stevenson and Dindal, 1985). In summer, *Aphodius* grubs hatch from eggs in three to five days, and the instars last two to four days (first instar), three to eight days (second), and three to five weeks (third) (Landin, 1961; Holter, 1975). In the Stevenson and Dindal microcosm study, they recognized that the diurnal temperature in the glass house was greater than the external environment and that growth rates of *Aphodius* larvae were proportional to temperature.

The larvae of *A. granarius* are typical of Scarabaeidae larvae, c-shaped with the abdomen folded against the fore part of the body. The larvae have a white body, a light brown head and six legs. The maximum reported head capsule width of *A. granarius* is a range of 1.42-1.68 mm (Tashiro, 1987). *A. granarius* larvae can be distinguished from other *Aphodius spp.* and *Ataenius spretulus* by the presence of palidia on the raster (Tashiro, 1987). The palidia make a distinct v-shaped pattern in the middle of the last venter and have random spines outside of the pattern. Larvae of the dung beetle *A. granarius* are found in pasture grasses in North America (Jerath and Ritcher, 1959).

In Ontario, Canada *A. granarius* larvae were found in June, peaked in early July, and declined by the end of July (Sears, 1978). In Ohio, larvae peaked during the first week of June and declined through the first week of July, indicating pupation (Niemczyk and Dunbar, 1976). In a laboratory setting, pupae from spring-collected adults that laid eggs, hatched and matured, averaged 9 days to complete the pupation process with the first adult of the new generation emerging on July 19 (Wilson, 1932). From the same New Jersey sheep pasture population the first pupae were observed on July 23 and the new generation adults emerged in large numbers during the second week of August. Newly emerged *A. granarius* adults are lighter in color (callow) than the parent generation, but turn dark shortly after emergence. Wilson found one generation of *A. granarius* per year in New Jersey with the adult overwintering (1932). In Ohio and Ontario, Canada, based on adult sightings in the spring and then again later in the year, it is suggested that *A. granarius* completes two generations per year but this is unconfirmed (Tashiro, 1987).

Adults of most species of *Aphodius* are dung feeders, but some also feed in decaying fungi or in decaying organic matter in or on the soil. The larvae include feeders on dung, organic matter, and live roots (Ritcher, 1966). Lugger (1899) observed *A.*

granarius larvae feeding on sprouting seeds of corn (*Zea mays* L.) in Minnesota. In turfgrass *A. granarius* and *A. pardalis* have been sited as pests because of their root-feeding activity (Ritcher, 1966; Woodruff, 1973; Sears, 1978). Turfgrass injury was caused on two mixed annual (*Poa annua* L.) and Kentucky bluegrass (*Poa pratensis* L.) fairways in Toronto, Canada during the 1976 and 1977 growing seasons (Sears, 1978). Damage to golf course turf in Michigan and Colorado was reported in 1978 and reports from Ohio indicate that *A. granarius* was present and causing injury in the early 1980's (Tashiro, 1987; Sears, 1978). To learn more about the life cycle of *A. granarius* in Michigan, this study initiated observations and sampling of adults and larvae at six golf courses from April through September during 1992 and 1993.

Ataenius spretulus

Ataenius spretulus (Haldeman) is in the order Coleoptera, family Scarabaeidae, subfamily Aphodiinae, and is commonly known as the black turfgrass *Ataenius*, or by turfgrass managers as simply *Ataenius*. Formerly, it was misidentified as *Ataenius cognatus* and described as such from specimens collected in Minnesota where *A. spretulus* is a common species (Woodruff, 1973). Although this beetle is classified as a dung beetle, turfgrass managers are familiar with it because of the injury it has caused on golf course turf (Borror, 1989; Sears, 1981; Kawanishi et al., 1974; Niemczyk and Dunbar, 1976; Weaver and Hacker, 1978). The first reported damage was to fairway turf in Minnesota in 1927 (Tashiro, 1987). It was not until after 1970 that reports of golf course turfgrass damaged by *A. spretulus* became more prevalent (Weaver and Hacker, 1978). Found in 41 states and with reported turfgrass damage from at least 23, *A.*

spretulus may be the most widespread white grub pest on golf courses in the United States (Niemczyk and Dunbar, 1976). The scope of turfgrass injury caused by *A. spretulus* in Michigan continues to be revealed.

A. spretulus is a shiny black beetle, approximately 5 mm long and 2.2 mm wide (Tashiro, 1987). *A. spretulus* overwinters as an adult (Weaver and Hacker, 1978). Hibernating adults have been found beneath dry cow dung, in waste piles of milorganite mixed with grass clippings, in leaf debris, in the first two inches of soil along golf course fairways, in the upper two inches of loose, well-drained soil at the edges of wooded areas and river banks (Weaver and Hacker, 1978; Wegner and Niemczyk, 1981). In Ohio, the onset of migration from overwintering sites occurs in early to late March with eggs first appearing in early to mid-May (Wegner and Niemczyk, 1981). They examined several specimens which revealed that 65% of all overwintering beetles were female, and 89.7% of those examined were inseminated. The females dissected in spring and summer had 12 ovarioles each containing three to four eggs in different stages of development. More than half of the females dissected in late May and June appeared to have oviposited already. The shiny, white, oval eggs are deposited in clusters of 11-12 in a cavity formed by the female in the lower 5 mm of thatch and upper 6 mm of soil among grass roots (Wegner and Niemczyk, 1981).

The adult beetles are easy to see crawling in the short-mowed turf on golf greens. The abundance of adults has not been correlated with the subsequent levels of grub activity within a certain site or region (Weaver and Hacker, 1978). It is believed that egg-laying in West Virginia occurs primarily from mid-May through early June and in the same periods in Ohio (Weaver and Hacker, 1978; Niemczyk and Wegner, 1979).

Eggs hatch soon after being deposited at the soil-thatch interface and larvae are present from late May to mid-July in Ohio, whereas, in West Virginia the researchers observed pupae and callow adults by late June (1978). Grub population densities associated with turfgrass have been reported as 100-150 per 0.1 m^2 in Connecticut, 200 – 300 per 0.1 m^2 in Ohio, and 500 larvae per 0.1 m^2 in Ohio (Niemczyk and Dunbar, 1976; Weaver and Hacker, 1978).

A. spretulus have three larval instars, typical of scarabaeid beetles (Tashiro, 1987). Head capsule widths grow from a mean of 0.5 mm in firsts, to 0.83 mm in seconds, and to 1.3 mm in third instars (Wegner and Niemczyk, 1981). Larvae are white, c-shaped grubs. The larvae do not have a distinct raster pattern, but there are 40-45 randomly placed hamate setae. The grubs have two pad-like structures on the tip of the abdomen between the setae and the anal slit, which helps to distinguish them from other scarab larvae (Wegner and Niemczyk, 1981).

According to Wegner and Niemczyk (1981), the period required for first generation *A. spretulus* to pass through one generation was 65 ± 5 days at soil temperatures of 25 ± 6°C. *A. spretulus* has one or two generations per year, depending on location and latitude (Tashiro, 1987). In Ohio and West Virginia, *A. spretulus* is bivoltine. In the latitude of western New York, Ontario, Canada, and Minnesota, *A. spretulus* are believed to be univoltine.

Wegner and Niemczyk performed the most thorough study on the life history of *A. spretulus* in the turfgrass environment. In fact, Tashiro (1987) touts their work as the most comprehensive study of any turfgrass scarabaeid in turfgrass soil throughout the season. Part of their study involved establishing a degree-day index for predicting *A.*

spretulus activity and development, and was based on a flight activity threshold of 13°C (1981). Insect models that use observations of one active growth stage to predict some future stage are usually successful (Pruess, 1983). The Ohio researchers used sampling techniques including light-traps, eight-vaned sticky cloth traps, soil samples pulled with a standard golf course cup-cutter, and flotation methods (1981).

In Michigan, superintendents consistently list *A. spretulus* as a serious pest (Smitley, 1994). Cautious superintendents will make one or two prophylactic insecticide treatments to prevent turf injury from the complex of scarab species when one-well-timed application could provide sufficient control (Nyrop et al., 1995). Michigan turfgrass managers suspected that there were two generations of *A. spretulus* per year based on many locations experiencing two separate periods of turf injury during the summer. The present study resulted from the need for additional information regarding the life cycle of *A. spretulus* in Michigan pertinent to its control.

Degree Days

Recognizing that *A. spretulus* and *A. granarius* are injurious pests of golf course turfgrass in Michigan, once their life cycles are better understood, a tool for predicting their occurrence and development would be beneficial for turfgrass managers. The complexity and variability in the biological world, the variability in potential strategies and the number of available tactics to reduce pest levels below economic levels requires an organized and structured approach (Gage, 1989). Part of a structured approach includes monitoring and sampling. Fine-tuning when these activities are best executed makes the tasks more efficient and saves resources.

The concept that growth and development of many organisms is dependent upon the amount of heat present in or around the organism allows us to develop temperature-derived indexes to predict that development. In general, it holds that the cooler the temperatures are, the slower is the rate of growth and development of plants and invertebrate animals (Zalom et al., 1983). Knowing that some insects develop at rates determined by temperature, the thermal unit of measure is in degree-days (DD) (Shetlar, 1991). Useful DD indexes have been established for other turfgrass insects including annual bluegrass weevil, hairy chinch bug and larger sod webworm (Shetlar, 1991; Tashiro, 1987).

Degree-days can be calculated in a multitude of ways. However, all methods of DD rely on the common principle that the biological process of interest will not begin until a certain temperature threshold is reached or exceeded. This threshold is known as the base temperature (Andresen, 1993). The selection of an appropriate base temperature is critical to the DD or any heat unit model (Yang et al., 1995). They feel that the methods commonly reported in literature for determining base temperatures are tedious and lack mathematical theory so they have proposed simple and mathematically-sound formulae to calculate the base temperatures for DD for organisms under study. Pruess (1983) may agree that the complexity of many DD models limits their application and validation. However, he recommends for practical application, that a standardized approach to establishing base temperature thresholds be instituted. To reduce the intimidation factor of sine wave approximations and different thresholds for every insect, Pruess proposes standardized thresholds of 5, 10 or 15°C for DD. Further, if standard thresholds are employed, the DD models are more likely to be employed where comparable temperature data are available. The minimum threshold assumption is that the biological process of interest will cease below the base temperature. In addition, there may be an upper threshold which is less well-defined but is often observed as the temperature above which the rate of development, or the process of interest (e.g., respiration, maturation) begins to decrease or stops (Zalom et al., 1983). Degree-days are calculated using observed daily temperature data relative to the base temperature, and upper temperature threshold if available. The state of development of the organism in question is usually correlated with the accumulation of daily DD through the growing season. For overwintering insects in Michigan this accumulation ends sometime in the late fall and normally begins again in the month of March (Andresen, 1993).

Several techniques are available for calculating degree-days through the use of daily maximum and minimum temperatures. From the simplest to the most complex, DD calculations include but are not limited to: averaging, single and double triangulation, sine wave, and modified sine wave (Allen, 1976; Zalom et al., 1983). These methods are considered linear models, because the rate of development is presumed to be a straight line directly related to temperature.

The simplest of the DD calculations is the average method, also referred to as the historical, simple, or mean-minus-base method (Pruess, 1983). To use this equation, the maximum and minimum temperatures are required to find the mean temperature, from which the base temperature is subtracted, (Max – Min)/2 - Base. The average method can underestimate DD when the minimum temperature is below the threshold, as is common in the spring and fall seasons. Another version of the average method is to set any minimum temperatures below the base threshold up to the base temperature before averaging. This would then be considered the modified average method (Andresen, 1993).

The most referenced method of calculating DD was derived by Baskerville and Emin (1969). The Baskerville-Emin method (BE) also known as the sine, or sine wave method assumes that the diurnal temperature curve is similar to the trigonometric sine curve. This method uses a day's low and high temperatures to create a sine wave over a 24-hour period, and then estimates DD for that day by calculating the area above the threshold and below the curve. This process weighs all temperatures during a day above the base in proportion to the amount of time the temperature actually exceeded the base temperature. This method is most important in the spring and fall when the minimum temperatures often fall below the base temperature. The BE method leads to more realistic DD totals than the average method. While this calculation requires a calculator with trigonometric functions and some skill to perform the tabulations, the BE values associated with various base temperatures have been formatted in look-up tables. Further, in Michigan DD derived by the BE method are readily available. A popular resource used by Michigan turfgrass managers is a weekly newsletter, the Crop Advisory Team Alert (CAT Alert) Landscape edition (MSU Extension IPM Program, East Lansing, MI). This newsletter is available printed or electronically on the worldwide web (www.msue.msu.edu/ipm). The DD values provided in the newsletter represent 32 stations throughout Michigan, and include Toledo, Ohio.

The use of automated on-site weather observation equipment by turfgrass managers is expanding. This equipment is typically capable of providing mean hourly temperatures and calculating DD based on direct integration of the hourly data. The direct integration method is the most realistic approximation of the actual amount of heat accumulated during a day vs. approximations calculated with daily maximum and minimum temperatures alone (Zalom et al., 1983). To calculate DD using hourly mean temperatures for a 24-hour period, the base temperature is subtracted from each of the hourly mean temperatures, all negative values set to zero and all differences summed. The total for the day is then divided by 24, the total number of observations. Pruess (1983) highly recommends that either the direct integration method, also referred to as actual DD method, or sine wave estimates of DD (BE) be used for the value of standardizing and making data more universally practical.

The DD indexes most commonly used are based on air temperatures. To encourage broader application of DD models, it is recommended that when developing prediction models, researchers use air temperatures obtained with equipment in locations comparable to temperatures operationally reported by the National Weather Service (NWS) (Pruess, 1983). This is because the NWS data are currently the most widely available. Further, soil and other micro-environmental records are encouraged during development of prediction models.

When an organism being studied resides in the soil environment, it seems logical that temperatures used for DD estimation would be more representative of the organisms' activity if they were measured in its immediate environment—the soil. However, this assumption did not hold for winter wheat (*Triticum aestivum* L.) phenology (McMaster and Wilhelm, 1998). Both air temperatures and near-surface soil temperatures were collected across the U.S. Central Great Plains to determine if predictions of winter wheat phenology could be improved when based on measured near-surface soil temperatures, closer to the shoot apex, rather than on air temperature. After evaluating multiple sites and thermal unit accumulation models, in no instance did soil temperatures significantly improve the prediction of winter wheat phenology.

The Northern masked chafer is a scarab pest of turfgrass that causes damage by feeding on roots (Tashiro, 1987). Air and soil based DD base 10°C are well correlated with the Northern masked chafer's first emergence from hibernation but are less useful for predicting the date of 50% and 90% flight (Potter, 1981).

On a golf course, knowing when scarab larvae were present in the soil and actively feeding on turfgrass roots would allow for more accurate and efficient sampling. Sampling confirms the need for management intervention to prevent turf injury or provides confidence that no intervention is necessary. Calendar dates have long been used for initiating control measures for insect pests while degree days (DD) are used in integrated pest management programs primarily to time sampling activities (Peterson and Meyer, 1995). Since many golf courses are equipped with on-site weather monitoring systems that calculate DD based on hourly data, and BE derived DD are readily available, in this study these indexes were correlated with observed biological activity of *A. granarius* and *A. spretulus*. Further, many of the life stages of *A. granarius* and *A. spretulus* occur in the soil. So, DD based on heat units accumulated in the soil were also related to these scarab insect life stages. The hypothesis is that DD indexes will be useful in predicting *A. spretulus* and *A. granarius* life stages, make scouting more efficient, and improve pest management decisions.

MATERIALS AND METHODS

On-Site and Regional Weather Observations and Degree-day Calculations

Activity of *Ataenius spretulus* and *Aphodius granarius* species were monitored at six golf course sites in Oakland County, Michigan during 1992 and 1993: Edgewood Country Club in Union Lake; Forest Lake Country Club in Bloomfield Hills; Tam O'Shanter Country Club in Orchard Lake; Franklin Hills Country Club in Franklin; Oakland Hills Country Club in Bloomfield Hills; and Orchard Lake Country Club in Orchard Lake. All six courses are located in the northern greater Detroit area and have a history of *Ataenius spretulus* infestations.

Weather data were collected at Edgewood Country Club, Forest Lake Country Club, and Tam O'Shanter Country Club in 1992 and 1993 from April 5 to September 30 using on-site EnviroCaster® equipment (Neogen, Inc., Lansing, MI). These three courses are located approximately 8 km from each other.

The EnviroCaster is a solar-powered, battery back-up, field installed micro-processor that collects data from a variety of sensors. The EnviroCaster processes weather data into models developed for predicting a variety of biological events. Air and soil temperature data were collected in this study. Temperature data were recorded by resistance thermometric devices (RTDs) that are made with a single platinum plate upon which the change in resistance is measured in response to temperature changes. Data were sampled by sensors every 15 minutes, averaged hourly, and stored in a 21-day memory file. Air temperatures were measured at a height of 0.3 m. Soil temperatures were monitored at 2.5 cm and 5.0 cm depths below a mix of irrigated Kentucky bluegrass and perennial ryegrass turf mowed at 5.0 cm at Edgewood and Tam O'Shanter Country

Clubs, and under irrigated annual bluegrass mowed at 1.3 cm at Forest Lake Country Club. In 1992, a portable soil temperature probe was periodically used to validate the accuracy of the permanently installed temperature probes. Repeatedly during the two seasons one or more of the sensors malfunctioned leaving gaps in the data sets. To estimate the missing data, linear regression analyses were run with the other two sites' data to approximate data at the missing station. The regression values that were used are listed in Tables A.1 - A.5 located in Appendix A. The best-fit regression values were used to interpret the missing data using the equation:

$$(y) = m(x) + b$$

> where y is the missing data point, m is the slope, x the known data point, and b the regression constant.

Of the 77,328 temperature measurements recorded in both years, an average of 6.7% of these were estimated (3% in 1992, 10% in 1993).

Hourly temperature data were downloaded from the EnviroCaster equipment at the three golf course sites weekly. Air temperature data were also obtained from the National Weather Service at two regional airports—Flint Bishop International Airport, Flint, Michigan and Detroit Metropolitan International Airport, Detroit, Michigan. The airport data are referred to as regional data in the following text. Flint Bishop airport is about 50 km north, while Detroit Metropolitan airport is about 40 km southeast of the golf courses sampled. In contrast to the golf course data, the National Weather Service observations are operationally taken in an open field in the middle of the airport runways at 1.5 m above the ground. Soil temperatures are not monitored at the regional airport locations.

For this study, it was deemed beneficial to pool the golf course temperature data for several reasons. The first was to compensate for estimated and missing temperature data due to season-long and intermittent probe failures among the sites. Further, the temperature data were ultimately compared to biological information. Scarab grubs are patchily distributed (Nyrop et al., 1995). Difficulty in obtaining adequate sample sizes of the grub species made it necessary for grub data to be pooled over six sites. The pooled temperature data were therefore considered most representative of the sampling area. In a study using DD for predicting sod webworm emergence, Tolley et al., 1986, found it more reliable to pool data for identifying adult peak flights.

Before pooling the temperature data from the three golf course sites, hourly temperature data for each variable at each of the golf courses were compared statistically to test for significant differences. The classical application of the analysis of variance or other tests for comparing sample means could not be directly applied because temperature data do not satisfy the assumption of independence (Wilks, 1995). That is, with classical statistics it is assumed that all the x_1 values are mutually independent and that the x_2 values are mutually independent. For the temperature data, the averages tested were time averages, and the residual violates the assumption of independence. Golf course temperature data, as paired variable and location, were tested for differences using the following equation (Wilks, 1995) appropriate for data with serial correlation, or time dependence:

$$z = \frac{[\bar{x}_1 - \bar{x}_2] - E[\bar{x}_1 - \bar{x}_2]}{[(s_1^2/n_1' + s_2^2/n_2') - 2\rho_{1,2}((s_1^2/n_1')^{1/2}(s_2^2/n_2')^{1/2})]^{1/2}}$$

where $\rho_{1,2}$ is the Pearson correlation between x_1 and x_2; n' is the effective sample size estimated using r_1, lag-1 autocorrelation coefficient; and the expected differences, between sites $E[\bar{x}_1 - \bar{x}_2]$ is assumed to be 0.

The approach chosen to address the problem of serial dependence was to determine an effective sample size, or equivalent number of independent samples, n'. That assumes that the fictitious sample size $n' < n$ of independent values, and that the sampling distribution of the average has the same variance as the sampling distribution of the average over the n autocorrelated values. It was assumed that the data for which n' was estimated followed a first-order autoregressive process, which are often reasonable approximations for representing the persistence of daily meteorological values (Wilks, 1995). Further, the persistence in a first-order autoregression is completely characterized by the single parameter ρ_1, the lag-1 autocorrelation coefficient, which was estimated from the data series using the sample estimate, r_1. The correlation r_1 was substituted for ρ_1 to estimate the effective sample size using the following approximation:

$$n' \cong n\,[(1 - \rho_1)/(1 + \rho_1)].$$

For each calendar date during the study, mean hourly temperatures for the variables air, soil at 2.5 cm, and soil at 5.0 cm were calculated from the three golf courses' data. These golf course (mean) data were subjected to analysis of variance for serial correlated data using the Wilks methodology described above. The air and soil data were compared to evaluate how differently they responded to weather-induced temperature fluctuations. Further, regional temperature data from DTW and Flint Bishop airports were compared to the golf course (mean) hourly air temperature using the same analysis appropriate for time dependent data described above.

A FORTRAN program (Appendix B) was used to calculate degree-day accumulations for air temperature, and soil temperatures at soil depths of 2.5 cm and 5.0 cm for a minimum development threshold temperature of 10° C (Kawanishi et al., 1974). Daily degree-day (DD) totals were obtained by integration of the average hourly temperatures above the threshold with all negative hourly totals set to zero. Seasonal accumulations for 1992 and 1993 data sets began on April 5 of both years. This DD calculation method is the most representative of the actual temperatures and periods of time they occur in the study area.

Degree-days at the airports were calculated and reported by the National Weather Service using the Baskerville-Emin (BE) method, which utilizes daily maximum and minimum temperatures. This method is the closest in accuracy to calculating degree-days with a 24-hour continuous sensor as was done at the golf course sites using the Envirocasters® (Andresen, unpublished data).

Sampling for *Ataenius spretulus* and *Aphodius granarius*

ADULT SAMPLING

Traps were used to monitor adult *A. spretulus* and *A. granarius* activity. Eight 2.54 cm by 2.54 cm wooden stakes equipped with metal clips to hold two, 15 cm by 15 cm cards coated with Tanglefoot® (Grand Rapids, MI), were erected at each golf course site. The sticky cards were attached to stakes 0.6 m above the ground (Wegner and Niemczyk, 1981). Traps were placed in the rough between fairways and in out-of-play, wooded areas where organic debris and duff had accumulated—typical of the beetles' overwintering habitat (Weaver and Hacker, 1978). Of the 48 traps, 16 were in natural areas and 32 were located in golf course roughs with maintained turf. Traps (sticky cards) were observed and beetles counted and identified weekly from April through September at the sites with EnviroCaster equipment, and May through August at the three other golf courses sampled during this study. Sticky cards were treated with an aerosol formulation of Tanglefoot® to maintain adhesive, or were replaced if *A. spretulus* or *A. granarius* beetles were on the cards, if they were heavily covered with other insects, had been broken, or were covered with grass clippings, leaves or other debris. On occasion the cards were broken by wind or knocked down by maintenance equipment. The total number of beetles caught per week was plotted with calendar dates and correlated to the accumulated DD.

LARVAE SAMPLING

A. spretulus and *A. granarius* larvae were sampled from six golf courses. At three sites, Oakland Hills Country Club, Orchard Lake Country Club, and Franklin Hills Country Club, soil samples were examined once per week for *A. spretulus* and *A. granarius* larvae from May through August. Samples were taken with a standard golf course cup cutter, 10.8 cm in diameter and 10 cm deep. Five samples were pulled from each of five plots in the fairway, and from each of five plots in the rough for a total of 10 plots and 50 soil cores per golf course. Each plot was 10 m x 5 m with 5 m between plots. Plots in the rough were directly across from plots in the fairway with a 3 m border on both sides of the fairway-rough interface before plots started.

At three other golf course sites larvae were sampled from one or two designated areas. At Edgewood Country Club soil core samples were taken from a practice chipping area consisting of a bentgrass putting green surface in 1992, and from the Kentucky bluegrass collar area around the practice green, which was mowed at rough height (5.0 cm) in 1993. At Forest Lake Country Club samples were taken from a 585 m^2 area across the 13th fairway in both years. Samples at Tam O'Shanter Country Club were taken from a 500 m^2 section of the 13th fairway in 1992 and from a 500 m^2 section of the 2nd fairway in 1993. Five samples were collected per week in 1992 and 10 cores per week in 1993 from each of the sample areas. Samples were examined for *A. spretulus* and *A. granarius* larvae by pulling them apart by hand. Soil cores were then reshaped and placed back into the ground. Plugs recovered and grew back within 2 weeks of sampling. Previously sampled turf plugs were avoided during subsequent sampling. Grubs collected from samples were counted, put into vials of KAA (kerosene, acetic acid, 95% ethanol, triton; Chu, 1973) and taken back to a laboratory for identification, measurement, and dissection under a microscope.

In 1992, to confirm that the method used for observing the soil cores was not overlooking beetle eggs or early instars, an effort was made to separate eggs and small larvae of *A. spretulus* and *A. granarius* using a rapid centrifugal flotation technique. This technique has been used for extracting nematodes from soil (Jenkins, 1964). No organisms of interest to this project were recovered so the method was not repeated.

The nature of Scarabaeidae infestations on golf courses poses many sampling problems (Wegner and Niemcyzk, 1981; Ives and Warren, 1965). Very low grub samples at the three courses equipped with Envirocasters® reflected this difficulty. Among the six courses studied, where grub populations were adequate, grub sampling revealed synchronized biological events. Therefore, to obtain adequate sampling sizes and because the sampling sites behaved alike, grub data from the six golf courses were pooled together.

The grubs were identified by the pattern of the setae on their rasters. *A. spretulus* larvae have a random pattern of 40 to 45 hamate setae on their rasters, while *A granarius* larvae have a v-shaped pattern of setae (Tashiro, 1987; Wegner and Niemczyk, 1981). Using a calibrated eyepiece micrometer, the head capsule of the grubs were measured and recorded according to the date of collection and location. In 1992, only grubs from the EnviroCaster-equipped sites were measured while in 1993 grubs from all six sampling sites were measured.

The incidence of *A. granarius* and *A. spretulus* larvae during each year was coupled with degree-day data for air temperature, soil temperature at 2.5 cm, and soil temperatures at a depth of 5.0 cm in 1992 and 1993. The incidence of *A. granarius* and *A. spretulus* larvae during each year were also correlated to regional DD data.

Soil samples were taken at the three EnviroCaster®-equipped golf courses from the areas sampled for grubs. Soil samples were analyzed for physical and chemical characteristics. Results of the soil analyses are presented in Tables C.1 and C.2 in Appendix C.

RESULTS AND DISCUSSION

1992 and 1993 Weather Data

Climatological records from the National Climatic Data Center show consistently below normal temperatures (-1.6 °C) for the state of Michigan from April-October 1992. There were even greater departures from normal for July-August (-2.6 °C), the two climatologically warmest months of the year (NOAA, 1993). In the 1993 study year, Southeast Lower Michigan averaged only slightly below normal temperatures (-0.08°C) from April-October, with July and August (1.2°C) slightly above normal (NOAA, 1994). Golf course temperature observations for this study are expressed in degree-days (DD) base 10°C beginning April 5 of the respective year. Regional temperature data are expressed as DD or DD BE (Baskerville-Emin, 1969). Consistent with the National Climatic Data Center, the accumulated DD for 1992 and 1993 at the golf course locations and two regional airports included in this study also verify that 1992 was the cooler season (Table 1). The greatest departure from normal and between years, occurred in the mid to late season, while May and June were cooler than normal but not greatly different between years.

Table 1. Degree-day data showing cooler conditions in 1992 than in 1993.

	Golf Course DD		Flint Bishop Airport DD BE		Detroit Metro Intern. Airport DD BE	
Date	**1992**	**1993**	**1992**	**1993**	**1992**	**1993**
May 1st	24	33	46	51	57	64
June 1st	164	176	227	215	238	254
July 1st	379	422	478	499	507	566
August 1st	660	796	781	904	836	1016
Sept 1st	910	1136	1052	1262	1131	1443
Sept. 30th	1090	1254	1256	1396	1344	1637

DD base 10°C beginning April 5 of the respective year.
BE method of DD calculation, Baskerville and Emin, 1969.

During 1992, air data from Edgewood Country Club, soil 2.5 cm data from Tam O'Shanter Country Club, and soil 5.0 cm data from Forest Lake Country Club could not be reported due to temperature probe failures.

The hourly temperature data for air, soil 2.5 cm, and soil 5.0 cm were compared among sites using paired variable and locations to test for significant differences. The statistics used were appropriate for serial correlated data which included the use of a lag-1 autocorrelation coefficient r_1, and an effective sample size n' (Wilks, 1995). The paired variable and location comparison results are located in Table 2.

Hourly temperature data collected at three golf courses with EnviroCaster® equipment for air, soil at 2.5 cm and soil at 5.0 cm at three golf courses were converted into degree-day units. Figure 1 represents the degree-day (DD) units for the available air, 2.5 cm soil and 5.0 cm soil from the three golf courses in 1992, and Figure 2 represents similar data for 1993. The similarities among the variables between the sites are apparent in these charts.

Table 2. Hourly temperature comparisons for air and soil at three golf courses. 1992 and 1993.

1992

Variable	**Location Pair**	**Z Statistic§**
Air T°	Forest Lake - Tam O'Shanter	1.232
Soil 2.5 cm T°	Edgewood - Forest Lake	-2.19*
Soil 5.0 cm T°	Edgewood - Tam O'Shanter	1.664

1993

Variable	**Location Pair**	**Z Statistic§**
Air T°	Edgewood - Forest Lake	-0.427
	Edgewood - Tam O'Shanter	4.166*
	Forest Lake - Tam O'Shanter	3.664*
Soil 2.5 cm T°	Edgewood - Forest Lake	0.624
	Edgewood - Tam O'Shanter	0.795
	Forest Lake - Tam O'Shanter	1.21
Soil 5.0 cm T°	Edgewood -Forest Lake	3.203*
	Edgewood - Tam O'Shanter	1.96
	Forest Lake - Tam O'Shanter	0.682

*Significant at the α .05 level
§Following Wilks' (1995) analysis for serial correlated data.

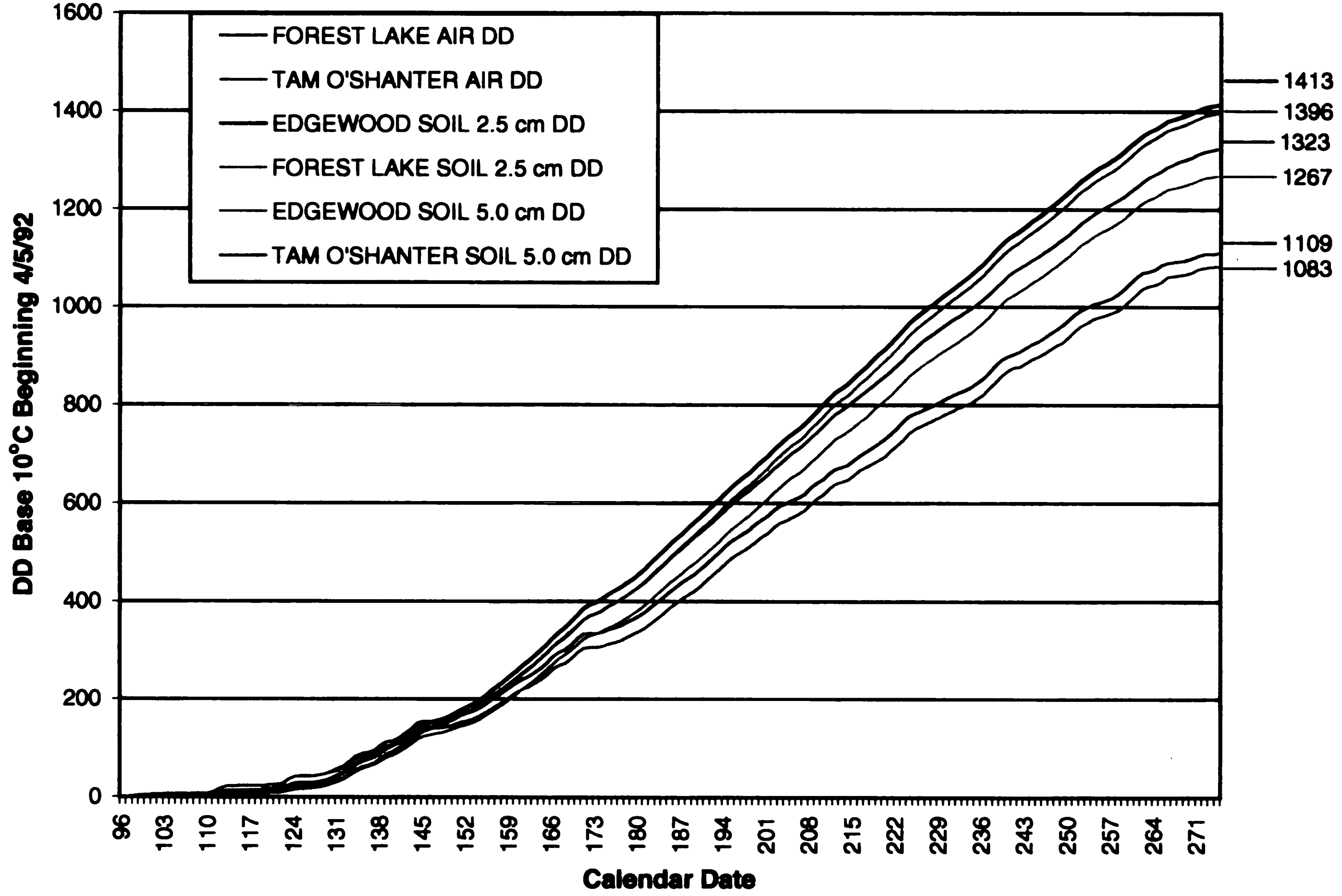

Figure 1. Air and soil DD for three golf courses. 1992.

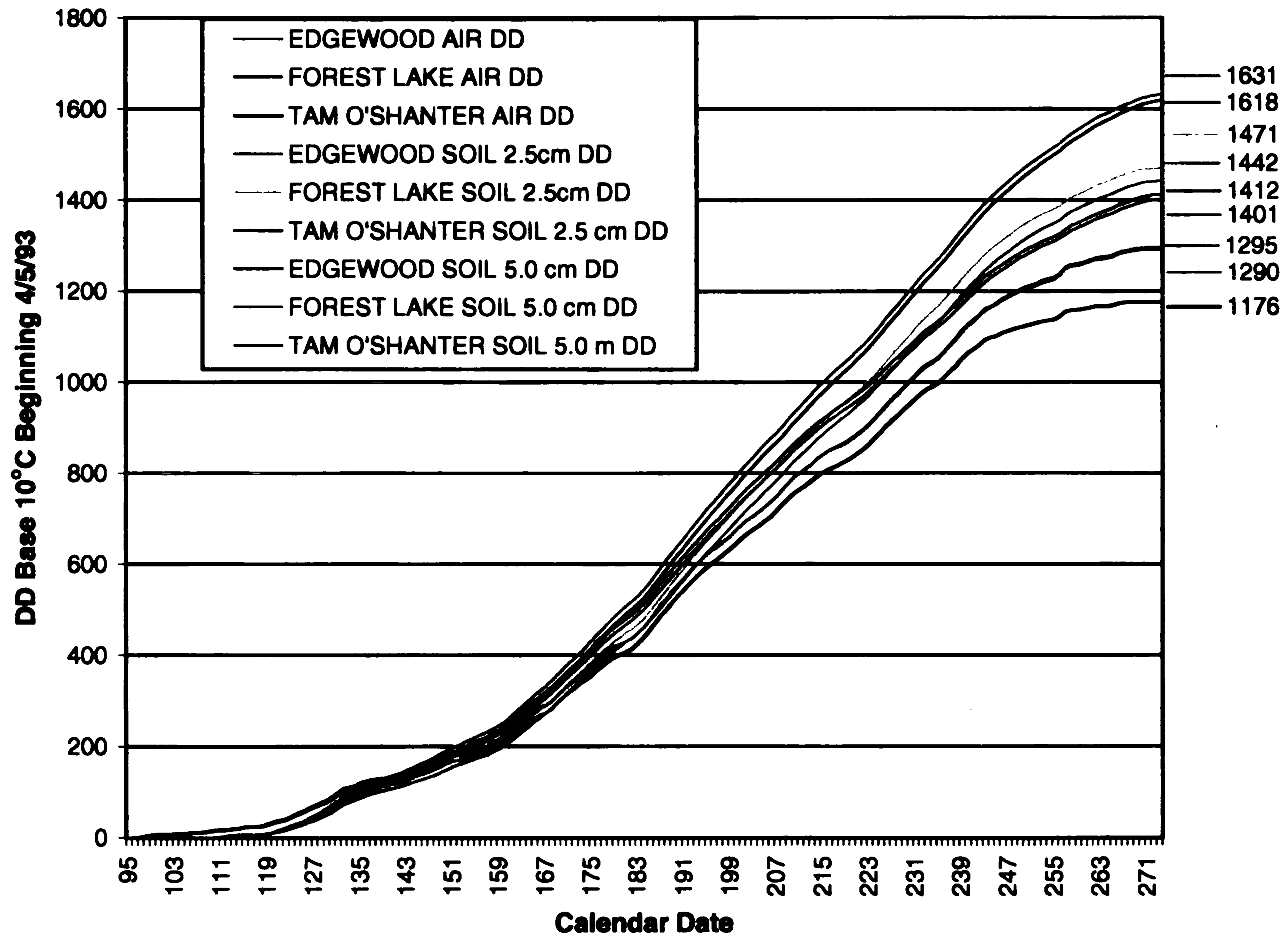

Figure 2. Air and soil DD for three golf courses. 1993.

For effective use of on-site weather data, placement of weather observation equipment should be representative of the property at large or placed near a location that historically had the first outbreak of a disease or insect in which the turf manager is interested in monitoring. When placing the units there should be no interference from buildings or other structures that may alter the wind, temperature, or moisture readings. The Envirocasters® at Forest Lake and Tam O'Shanter Country Clubs were free from obstruction. Forest Lake Country Club soil probes were placed at the edge of a fairway and the primary housing unit with the relative humidity/air sensor was in the rough 7.5 m east of the maintenance building. The one-story building did not cast shade on the unit. Tam O'Shanter Country Club's Envirocaster® was centrally located on the golf course in a sod nursery. Security from vandals for the weather station at Edgewood Country Club took priority over placement in a representative or unobstructed site. The unit was situated close to maintenance buildings that could have influenced the readings compared to the golf course at large. The total DD from Edgewood County Club were slightly greater than the other sites as seen in Figures 1 and 2. Table 3 provides the total DD on the last calendar date of the project for each golf course and variable measured.

Table 3. Total DD for air and soil at three golf courses. 1992 and 1993.

		Location and Total DD September 30, 1992 and 1993		
Variable	**Year**	**Edgewood**	**Forest Lake**	**Tam O'Shanter**
Air	**1992**	NA	1099	1083
	1993	1290	1295	1176
Soil 2.5 cm	**1992**	1413	1267	NA
	1993	1631	1471	1412
Soil 5.0 cm	**1992**	1396	NA	1323
	1993	1618	1442	1401

NA – Data not available.
*DD base 10°C beginning April 5 of the respective year.

While some of the sites' temperature data were significantly different at the α .05 level, the majority are not significantly different (Table 2). Due to missing and estimated data as a result of faulty probes, and the difficulty in obtaining effective sample sizes of the grubs under study, it was deemed beneficial to pool the sample data rather than to evaluate the variables and locations individually.

Mean hourly temperatures were calculated for each variable using data from the three golf courses with Envirocasters® for both 1992 and 1993. These pooled data were used to statistically compare the air temperatures with the soil temperatures at 2.5 cm and 5.0 cm depths. The results are listed in Table 4 and are consistent with patterns normally observed between air and soil temperatures. Over the season, the air temperatures were significantly cooler than the soil temperatures at 2.5 cm and 5.0 cm depths. The soil temperatures at 2.5 cm and 5.0 cm depths were not significantly different.

Table 4. Golf course air and soil hourly temperature comparisons. 1992 and 1993.

1992	Variable Pair	Z Statistic§
	Air - Soil 2.5 cm	-3.056*
	Air - Soil 5.0 cm	-3.456*
	Soil 2.5 cm – Soil 5.0 cm	0.335
1993	**Variable Pair**	**Z Statistic§**
	Air - Soil 2.5 cm	-2.211*
	Air - Soil 5.0 cm	-2.043*
	Soil 2.5 cm – Soil 5.0 cm	-1.012

* Significantly different at α .05.
§Following Wilks' (1995) analysis for serial correlated data.

Table 5 summarizes the mean temperatures and standard deviations (SD) for air and soil depths of 2.5 cm and 5.0 cm at each of the golf course locations. The greatest variability occurs in the air temperature data for 1992 with SDs of ± 6.58 to 6.75. In 1993, the soil at 2.5 cm shows the greatest variability with SDs of ± 7.91 to 8.57. The 5.0 cm soil data exhibit the greatest consistency in both years with a maximum SD of ± 5.23 in 1992, and 6.25 in 1993.

As with the site-specific air and soil DD, the golf course (mean) DD for air and soil at 2.5 cm and 5.0 cm depths were plotted with calendar dates in Figures 3 and 4 for 1992 and 1993, respectively. In April and May during both years the DD accumulation for the soil is slower than for air. As the seasons progressed, the soil DD surpassed the accumulated air DD at the end of May (calendar dates 148 in 1992, and 150 in 1993). Once soil temperatures increased, the soils' capacity to retain heat allowed more DD to accumulate over longer periods in contrast to air temperatures that fluctuated more rapidly (Hanks, 1992).

Table 5. Air and soil temperature data for three golf courses. 1992 and 1993.

1992

Location	**Variable**	**Mean ± SD**	**Total DD**
Edgewood	Air	NA	Σ Air DD = NA
	Soil 2.5 cm	17.57 ± 5.28	Σ Soil 2.5 cm DD = 1413
	Soil 5.0 cm	17.46 ± 5.23	Σ Soil 5.0 cm DD = 1396
Forest Lake	Air	15.3 ± 6.58	Σ Air DD = 1099
	Soil 2.5 cm	16.69 ± 5.29	Σ Soil 2.5 cm DD = 1267
	Soil 5.0 cm	NA	Σ Soil 2.5 cm DD = NA
Tam O'Shanter	Air	15.05 ± 6.75	Σ Air DD = 1083
	Soil 2.5 cm	NA	Σ Soil 2.5 cm DD = NA
	Soil 5.0 cm	17.07 ± 5.01	Σ Soil 5.0 cm DD = 1323

1993

Location	**Variable**	**Mean ± SD**	**Total DD**
Edgewood	Air	16.43 ± 7.1	Σ Air DD = 1290
	Soil 2.5 cm	18.17 ± 8.45	Σ Soil 2.5 cm DD = 1631
	Soil 5.0 cm	18.55 ± 6.25	Σ Soil 5.0 cm DD = 1618
Forest Lake	Air	16.5 ± 6.99	Σ Air DD = 1295
	Soil 2.5 cm	17.28 ± 8.57	Σ Soil 2.5 cm DD = 1471
	Soil 5.0 cm	17.73 ± 5.65	Σ Soil 2.5 cm DD = 1442
Tam O'Shanter	Air	15.68 ± 7.02	Σ Air DD = 1176
	Soil 2.5 cm	16.89 ± 7.91	Σ Soil 2.5 cm DD = 1412
	Soil 5.0 cm	17.42 ± 5.42	Σ Soil 5.0 cm DD = 1401

NA – Data not available.
DD base 10°C beginning April 5 of the respective year.

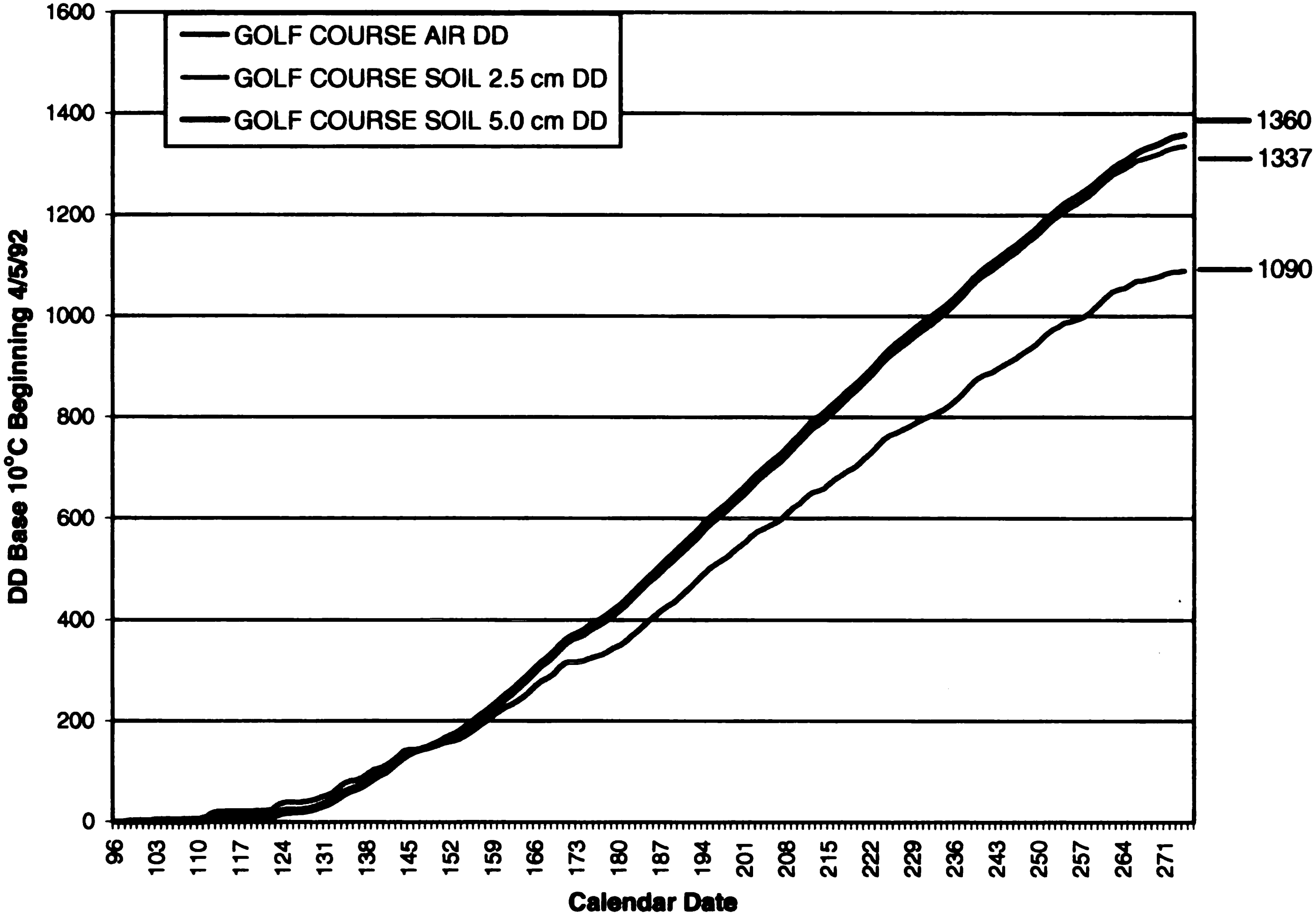

Figure 3. Golf course (mean) air and soil DD. 1992.

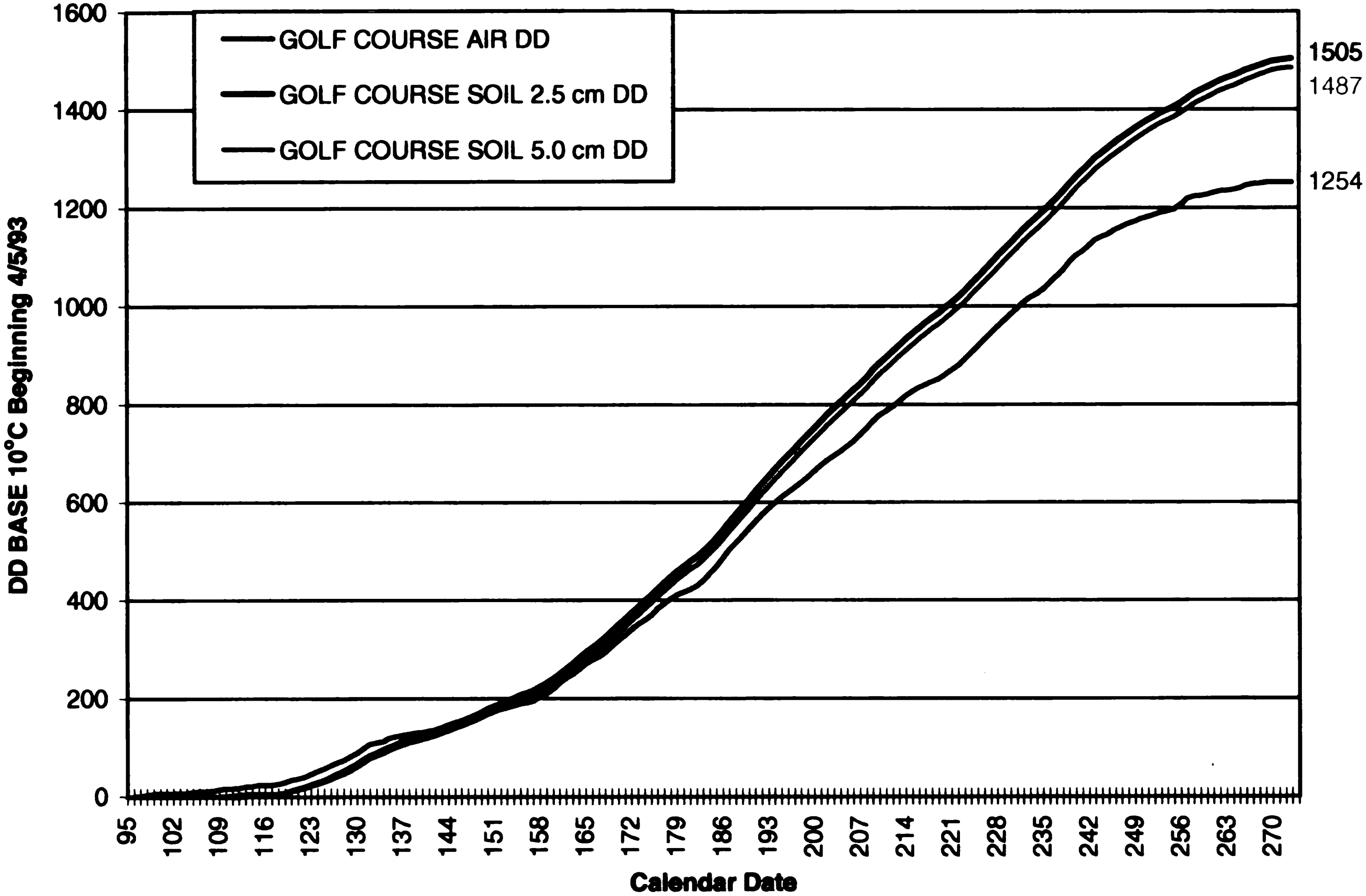

Figure 4. Golf course (mean) air and soil DD. 1993.

Golf course (mean) hourly air temperatures and regional (airport) hourly air temperatures from April through September were statistically analyzed using Wilks' methodology for serial correlated data (Table 6). In both 1992 and 1993, the golf course temperatures were significantly cooler than temperatures observed at DTW airport. The golf course temperatures were cooler but not significantly different than those observed at Flint Bishop airport in either year. The two airport temperature data sets were significantly different from each other both years with DTW consistently reporting warmer temperatures during the study period.

Table 6. Golf course and regional airport hourly air temperature comparisons. 1992 and 1993.

1992

Paired Locations	Z Statistic§
Golf Course - DTW	-3.913*
Golf Course - Flint	-1.926
DTW - Flint	2.459*

1993

Paired Locations	Z Statistic§
Golf Course - DTW	-8.321*
Golf Course - Flint	-0.376
DTW - Flint	5.383*

*Significant at α .05 level
§Following Wilks' (1995) analysis for serial correlated data.

After hourly temperature comparisons were made between the golf course and regional data, the regional DD BE base 10°C were plotted with golf course air DD for 1992 and 1993 in Figures 5 and 6, respectively. The DTW site had the highest DD accumulations, which would be expected. DTW is the farthest south location and is the

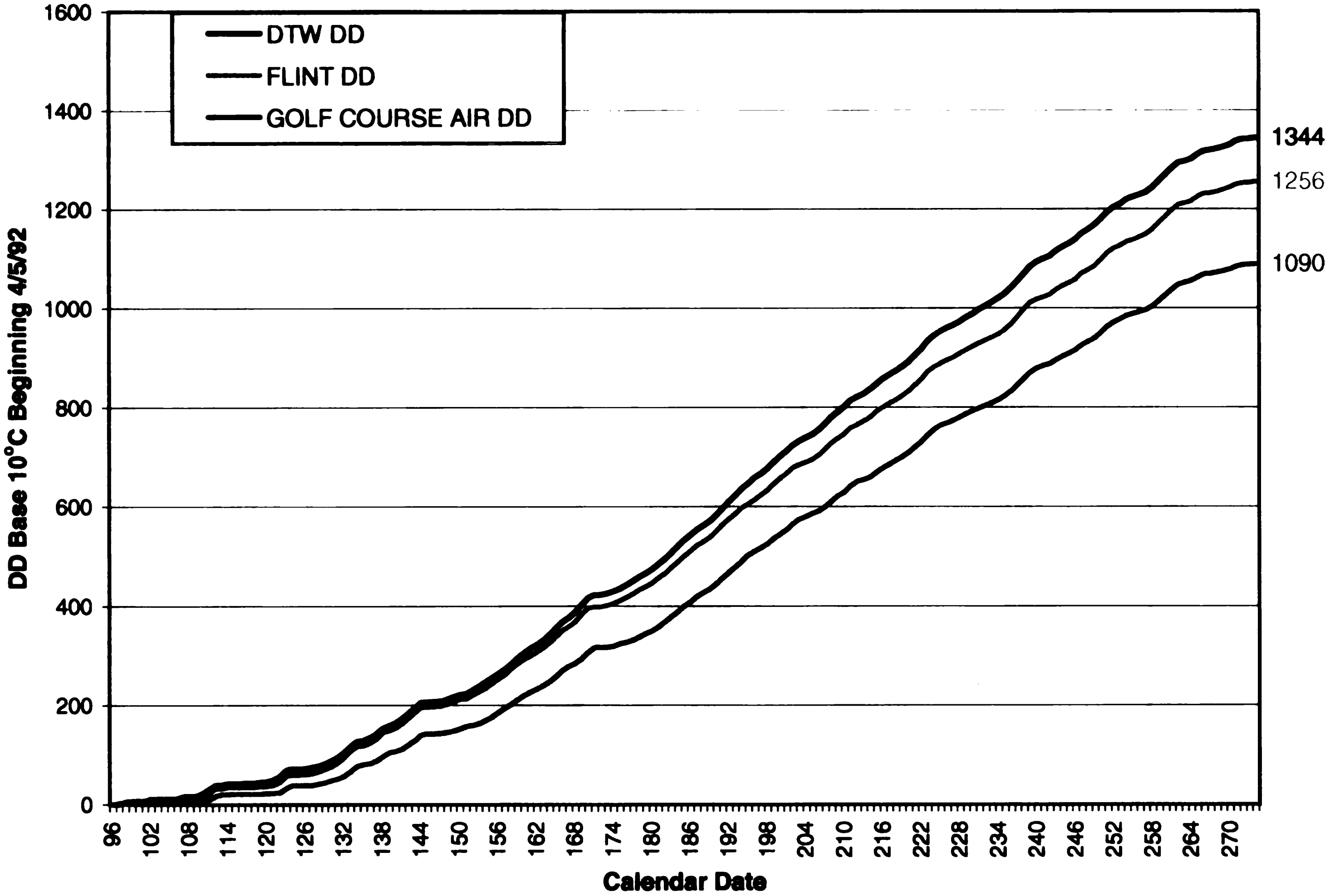

Figure 5. Regional and golf course air DD. 1992.

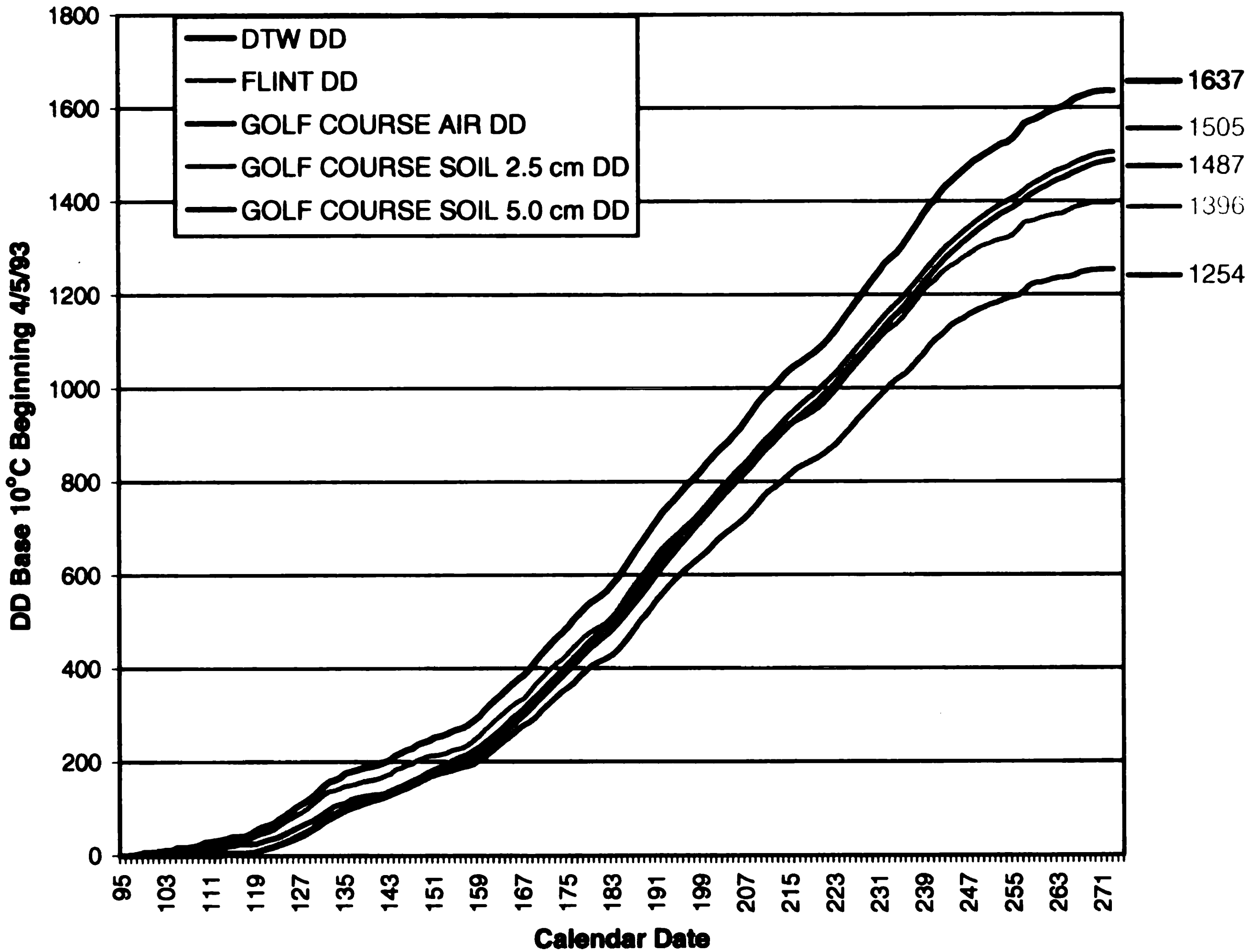

Figure 6. Regional and golf course air and soil DD. 1993.

site with the greatest amount of urbanization—more paved vs. vegetated surfaces. In general, paved surfaces gain and lose heat more slowly than vegetated surfaces (Hanks, 1992), possibly contributing to warmer temperatures overall. Although located farther north, accumulated DD from the Flint Bishop airport were also greater than the golf course DD. The same reasons that DTW was warmer may also hold true for the Flint site—an abundance of paved surfaces near the station vs. the turfgrass on and around the golf course sites, which are affected by the cooling of evapotranspiration. (Beard, 1973)

Figure 5 illustrates that the 1992 departure of DTW and Flint's DD above golf course DD occurred at the end of April-early May, calendar dates 117-124. The DTW and Flint DD began departing from each other at about two months later, approximately calendar date 173. Season-long DD values were 1344 for DTW; 1256 for Flint, and 1090 for golf course air.

Figure 6 shows all the 1993 variables—air and soil 2.5 cm and soil 5.0 cm—from the golf course DD data set plotted with the regional DD. As in 1992, the regional DD began departing from the golf course air DD in early May, around calendar date 125. The departures between the two regional data sets are less dramatic than in 1992 but are still significantly different (Table 6). The total DD accumulated by golf course soil at both 2.5 and 5.0 cm depths exceeded the Flint DD but were less than the DTW total DD in 1993. The soil 2.5 cm DD surpassed Flint DD in mid-July, calendar 201, whereas the soil at 5.0 cm DD took until August 4 (calendar 216) to exceed them.

For turfgrass managers, site-specific data would be desirable for obtaining temperature data pertinent to pest management. If located properly, data generated from on-site sensors best represents local conditions allowing for more precise and informed decision-making. Turf managers using airport based weather observations in their region should recognize that airport data will likely report higher temperatures than what occurs on the golf course. Adjustments should be made to compensate for differences in the environments where the temperature observations are taken, i.e., bare ground and paved surfaces at the airports vs. turfgrass covered areas.

Movement of Adult *Ataenius spretulus* and *Aphodius granarius* on Golf Courses

In April 1992 and 1993, sticky card traps were erected to monitor the adult flight activity of *Ataenius spretulus* and *Aphodius granarius*. Figures 7 (1992) and 8 (1993) show the periods when the adults of these two beetles were actively flying. No *A. granarius* beetles were trapped in 1992 and very few were trapped in 1993. There was not much flight activity by either species in 1993 between days 134 and 144 when it was cool. During this period only an average of three DD accumulated per day.

Trap numbers indicate that there was an early and a late season flight of *A. spretulus*. The first flight period reflects the time when the beetles moved between winter and summer habitats and were looking for oviposition sites. Based on work done by Wegner and Niemczyk, approximately 65% of all overwintering beetles are females and almost 90% of those examined in April were already inseminated. So, spring is apparently not when the beetles mate. The second period of flying activity was by the generation of insects hatched during the current season. Beetles flying in August or September may be heading for over-wintering habitat, or looking for oviposition sites.

Table 7 provides information about the spring and fall flight periods for *A. spretulus* and Table 8 presents similar data for *A. granarius*. In 1992, the spring *A. spretulus* flight lasted 7 weeks while 290 air DD accumulated. The 1993 flight lasted almost twice as long as in 1992 and nearly twice as many DD accumulated during that period. Considering that in 1992 Michigan experienced below normal temperatures climatologically (NOAA, 1993), the beetles from the 1992 generation may have overwintered in a less mature state than in a normal year and required additional time and heat to complete development, or mating and ovipositing in 1993. The first adult *A.*

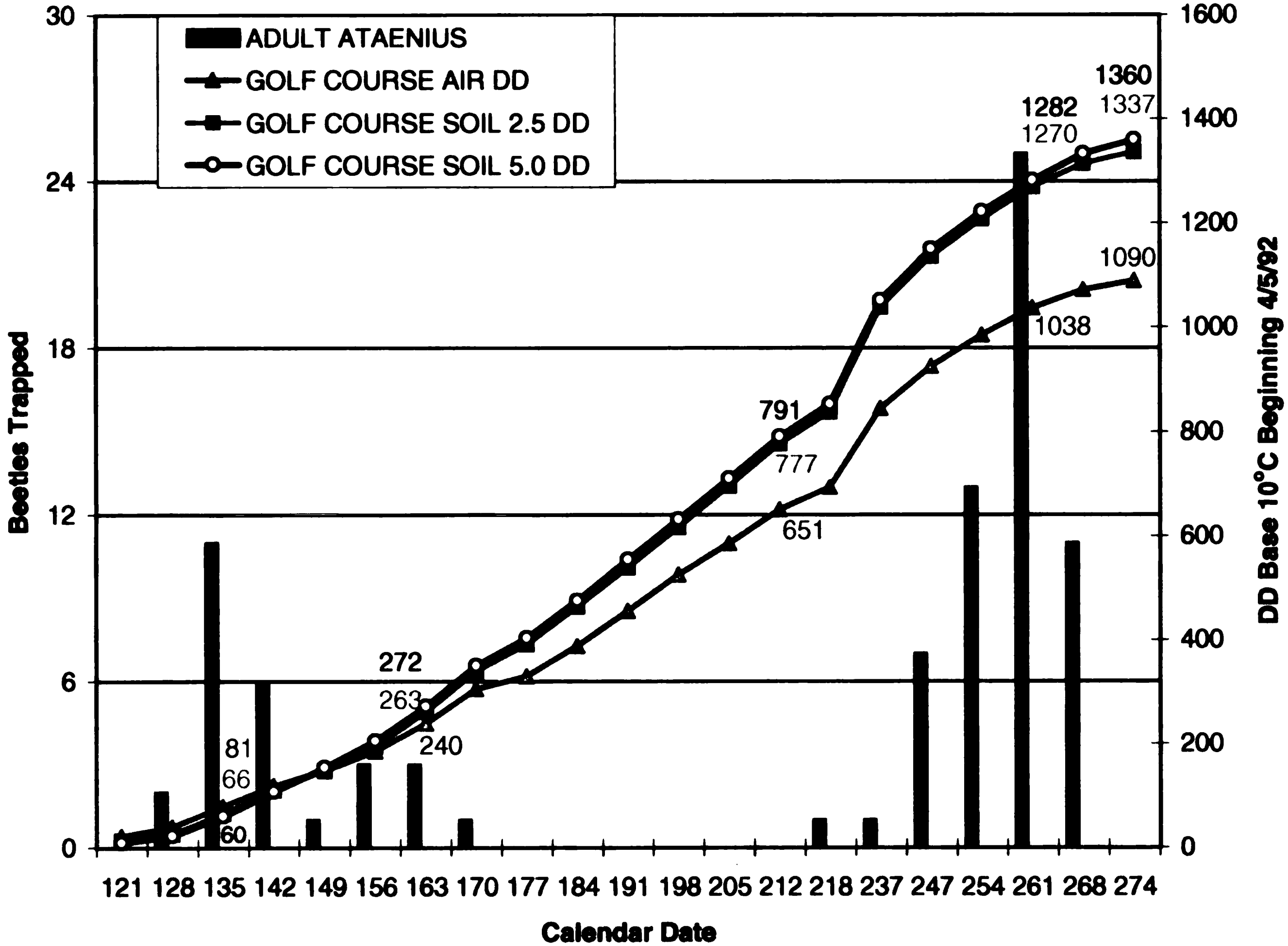

Figure 7. Total adult *Ataenius spretulus* and golf course air and soil DD. 1992.

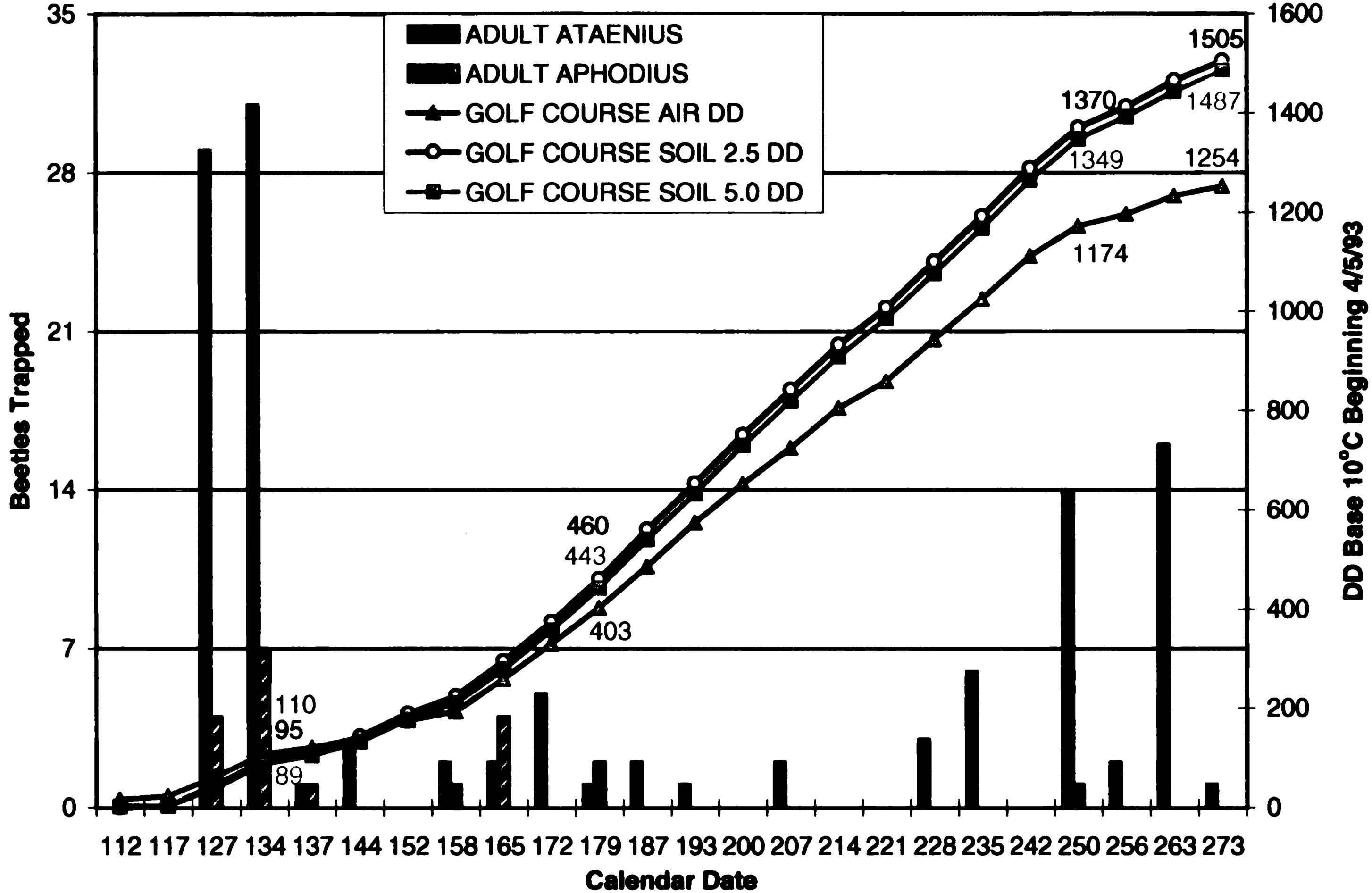

Figure 8. Total adult *Ataenius spretulus* and *Aphodius granarius* and golf course air and soil DD. 1993.

spretulus beetles trapped in both 1992 and 1993 occurred the same calendar week (124-131) although the 1992 air DD base 10°C were only 60% of those for the same week in 1993. This may suggest that something other than air temperature incites emergence from overwintering sites. Figures 7 (1992) and 8 (1993) plot adult *A. spretulus* and *A. granarius* flight activity with golf course air DD.

Table 7. Flight activity of adult *Ataenius spretulus* and golf course air DD. 1992 and 1993.

Spring Flight-Year	Beginning Date	Beginning DD	End Date	End DD	Duration	DD accumulated during flight
1992	128	41	177	331	49 days	290
1993	127	64	200	652	73 days	588

Fall Flight-Year	Beginning Date	Beginning DD	End Date	End DD	Duration	DD accumulated during flight
1992	218	694	274	1090	56 days	396
1993	207	725	273	1254	66 days	529

Table 8. Flight activity of adult *Aphodius granarius* and golf course air DD. 1993.

Spring Flight-Year	Beginning Date	Beginning DD	End Date	End DD	Duration	DD accumulated during flight
1992	No adults trapped.					
1993	127	64	187	486	60 days	422

Fall Flight-Year	Beginning Date	Beginning DD	End Date	End DD	Duration	DD accumulated during flight
1993	250	1113	NA-The only beetle trapped was on date 250.			

The soil DD during the same calendar period (124-131) when the initial flight occurred were 27 at soil 2.5 cm in 1992, and 45 in 1993; 20 at soil 5.0 cm in 1992 and 41 in 1993. As with the air DD, the soil DD in 1993 were greater than those in 1992 the week that adult beetles were first trapped in this study.

Because DD indexes are useful indicators of biological development of some insects and plants (Richmond and Shetlar, 1996; Branham and Danneberger, 1989) the difference in the DD associated with flight activity between 1992 and 1993 was enigmatic. The thought occurred that the beetles may be developing and behaving in response to DD units not only from the current season but also from the thermal units to which they were exposed as adults the season prior to their overwintering. To investigate this theory, DD from summer and fall 1991 were counted with spring 1992 DD. Also, DD of summer and fall of 1992 were combined with spring 1993 DD. These DD combinations were then evaluated in relation to spring flight information. The Flint Bishop airport DD data were used for this comparison because it was available for reference from 1991 and through the study period. Further, the Flint temperature data were not statistically different from the golf course air DD (Table 6).

In 1991, 1,004 DD BE base 10°C accumulated between calendar date 212 and 269 at the Flint airport. This would have been the approximate period when the 1991 *A. spretulus* adult generation were exposed to thermal units prior to seeking overwintering habitat in the fall. Based on Flint DD in 1992, 358 DD accumulated during the *A. spretulus'* spring flight following the 1991 late season accumulation of 1,004 DD for a combined total of 1,362 DD. In 1993, 659 DD accumulated during the spring flight following the 1992 late season DD accumulation of only 474 DD for a combined DD of 1,133. By considering the DD from the late summer and fall seasons prior to the 1992 and 1993 spring adult flight activity, there was a smaller difference in the total DD than when only the spring seasons' DD were compared, i.e., 229 vs. 301. Although these DD totals did not include temperatures exceeding the 10°C threshold in October through

March, this may suggest that temperatures in the seasons preceding spring emergence might be a factor to consider in the developmental and mating stage of the beetles and thus their spring activity. Overall, this approach did not increase our confidence in the DD data and its correlation with the biological activity of *A. spretulus* and *A. granarius*.

When comparing the 1992 and 1993 *A. spretulus* fall flight periods, the duration is nearly the same with 1992 lasting 8 weeks (56 days) and 1993 lasting just over 9 weeks (66 days). The 1993 DD are about 25% greater than in 1992 during the fall flight periods (Table 7).

Tables 9 and 10 present the *A. spretulus* trap and flight period information in relation to the larval observations. In 1992, there were 46 days between the first adult *A. spretulus* trapped and the first grub collected. In 1993, there were only 17 days between these same events. If adult trap catches (averaged over all 6 sites) indicate oviposition activities, then the 1992 oviposition period was shorter (7 weeks) than the 1993 oviposition period (10.4 weeks). In 1992 there were 67 days between peak *A. spretulus* adult trap numbers and the peak grub numbers. During this 67-day period DD totals were 485 for air, 597 soil 2.5 cm; and 601 soil 5.0 cm. In 1993, 73 days passed between the peak *A. spretulus* adult trap numbers and peak grub sampling data. During this 73-day period DD totals were 615 for air; 747 for soil cm; and 731 for soil 5.0 cm. Wegner and Niemcyzk (1981) determined that in their Ohio golf course study the period required of *A. spretulus* to pass through one generation was 65 ± 5 days at soil temperatures of 25 ± 6°C (range = 13 to 38°C), based on first generation periods estimated from life sampling data. Their first generation periods were determined as the number of days between appearances of first and second-generation eggs in samples.

Table 9. ***Ataenius spretulus*** **adult trap data related with grub observations and golf course air DD. 1992.**

	1992 Calendar Date	Air DD	DD Since 1st Adult Trapped	DD Since Peak Adult Trap
1st adult trapped	128	41	-	-
Peak adult trapped	135	81	40	-
1st grubs collected	174	319	278	238
Peak grub collection	202	566	525	485

Table 10. ***Ataenius spretulus*** **adult trap data related with grub observations and golf course air DD. 1993.**

	1993 Calendar Date	Air DD	DD Since 1st Adult Trapped	DD Since Peak Adult Trap
1st adult trapped	127	64	-	-
Peak adult trapped	134	110	46	-
1st grubs collected	144	123	59	13
Peak grub collection	207	725	661	615

In Michigan during this study, eggs were found only at Edgewood Country Club while sampling on calendar 165 and 172, 1993, and there were no indications of a second generation in either year. The first pupae found at this same site (Edgewood) was on calendar 200, 1993. Pupae were found up to day 228 and a callow adult was found on day 235, 1993—5 weeks after the first pupae sighting.

Table 11 provides the 1993 adult *A. granarius* trap information for spring activity which lasted 60 days (8.6 weeks) during which time 422 air DD accumulated. There were 31 days between peak *A. granarius* adult trap numbers and peak grub sampling numbers. During this 31-day period the total DD were 150 for air; 199 for soil 2.5 cm; and 190 for soil 5.0 cm. Thirty-one days from peak *A. granarius* adult trap numbers to peak grub activity is less than half the number of days that the *A. spretulus* took between peak adult trap numbers and peak grub activity; 67 and 73 days in 1992 and 1993, respectively.

Table 11. *Aphodius granarius* adult trap data related with grub observations and golf course air DD. 1993.

	1993 Calendar Date	Air DD	DD Since 1st Adult Trapped	DD Since Peak Adult Trap
1st adult trapped	127	64	-	-
Peak adult trapped	134	110	46	-
1st grubs collected	144	123	59	13
Peak grub collection	165	260	196	150

Eighty days passed between the peak adult *A. granarius* trapping and the last *A. granarius* grub found in soil samples. *A. granarius* grubs were found for 10 weeks, yet the peak grub numbers occurred three weeks after the first grub sighting. Although the time required for completion of one generation of *A. granarius* appears to be shorter than for *A. spretulus*, there was no evidence of a second generation by *A. granarius.* In 1998, when temperatures for the January-October period in the East North Central U.S. were 2.2°C above normal (NOAA, 1998), there was no evidence of a second generation of *A. granarius* observed at golf courses that had a first generation (Forest Lake CC). As was observed by Woodruff in New Jersey (1973), *A. granarius* appear to be univoltine in Michigan.

The number of adult insects trapped in the late summer and early fall of 1992 compared to the number of grubs observed during June and July, reveals that there were 9% adult *A. spretulus* (58 adults, 613 grubs) and no adult *A. granarius* (0 adults, 283 grubs) trapped. In 1993, late season adult trap numbers compared to the summer grub counts revealed that 18% *A. spretulus* (42 adults, 228 grubs) and 0.4% *A. granarius* (1 adult, 256 grubs) were trapped while flying. From these observations *A. granarius* appear to be less active fliers than the *A. spretulus* beetle.

There appears to be no relationship between the number of adult *A. spretulus* or *A. granarius* trapped at a given site with the number of grubs found at that same site.

Instars, Sizes and Occurrence of *Ataenius spretulus* and *Aphodius granarius* Larvae

Using an eyepiece micrometer, the head capsules of 61 *A. spretulus* grubs were measured in 1992 and the head capsules of 209 grubs were measured in 1993. The head size data from these two years were analyzed statistically. There were no significant differences in the head capsule sizes between years with F = 3.70, P-value = 0.056, and F critical = 3.88. Using the frequency of the head capsule sizes, a histogram (Figure 9) was created and determination of size ranges per instar determined for *A. spretulus* collected in 1992 and 1993.

Dimensions of the three instars for both *A. spretulus* and *A. granarius* are presented in Table 12. Only one specimen of a first instar *A. spretulus* was collected and it's head capsule measured 0.58 mm. The mean size *A. spretulus* second instar was 0.85 mm ± 0.07 and the mean size of the third instar was 1.32 mm ± 0.062. Head capsule widths of *A. spretulus* larvae collected in Ohio (Wegner and Niemczyk, 1981) averaged 0.5, 0.83, and 1.3 mm, respectively for the three instars based on 20 specimens per life stage. Although similar, apparently some variation in life stage sizes exists between populations.

Figure 10 is a histogram representing the size (mm) frequency of all *A. granarius* measured. In 1992, 61 *A. granarius* head capsules were measured, while 266 were measured in 1993. Only one specimen of a first instar *A. granarius* was collected and it's head capsule measured 0.7 mm. The mean size *A. granarius* second instar was 1.02 mm ± 0.069, and the third instar was 1.53 mm ± 0.079.

When comparing the two species of grubs, *A. granarius* is larger than *A. spretulus* during each of the three instars. Based on this project's sampling and mean sizes, the *A. granarius* first instar head capsule was 0.12 mm larger than *A. spretulus*, 0.17 mm larger in the second instar, and 0.21 mm larger in the third instar.

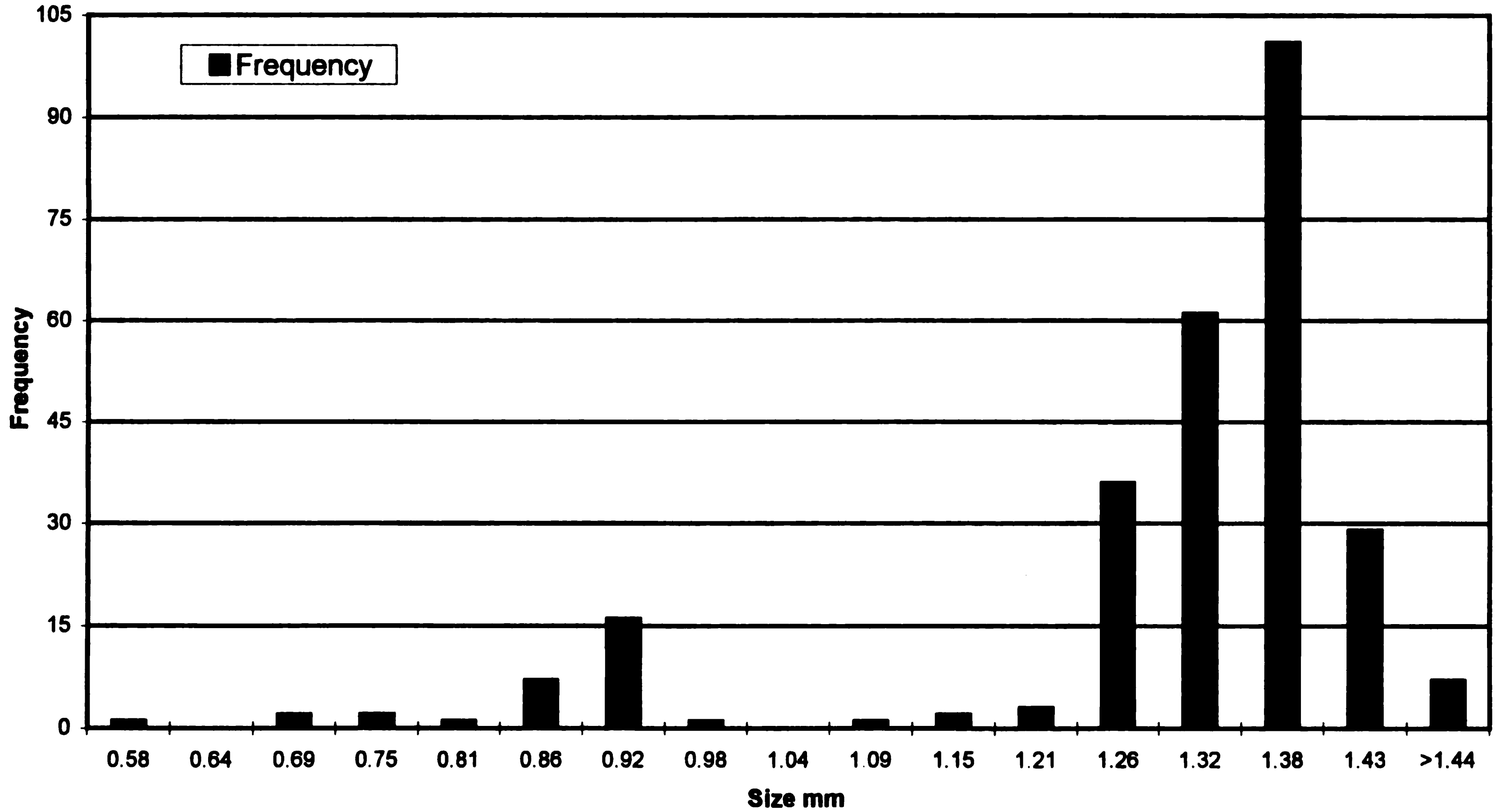

Figure 9. ***Ataenius spretulus*** **head capsule size frequency.**

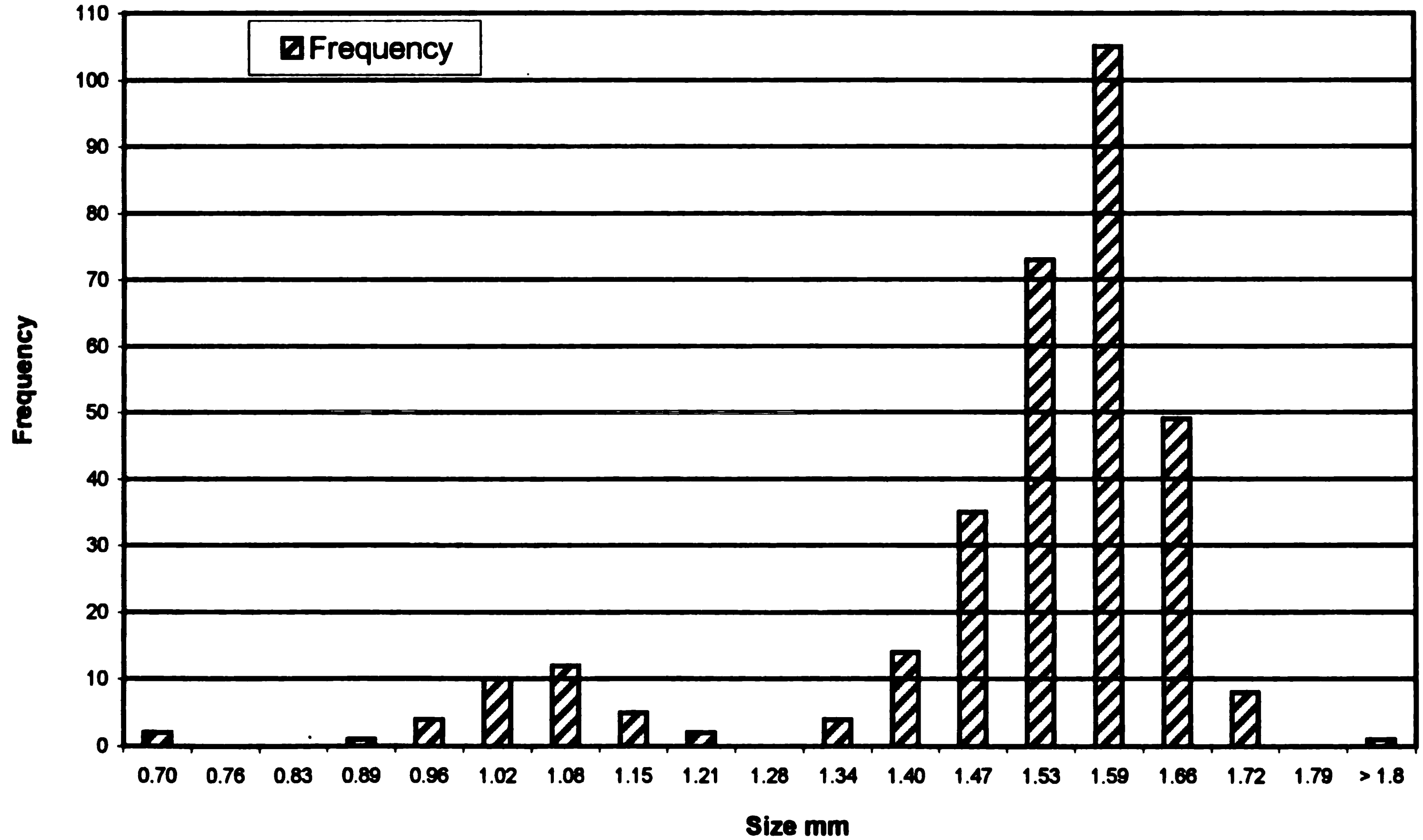

Figure 10. *Aphodius granarius* head capsule size frequency.

Table 12. Dimensions of *Ataenius spretulus* and *Aphodius granarius* instars based on measurements (millimeters).

Ataenius spretulus	**Head Capsule Width**	
Life Stage	**Range**	**Mean ± SD**
Instar 1	0.58	
Instar 2	0.63 –0.98	0.85 ±0.076
Instar 3	1.09 – 1.43	1.32 ± 0.062

Aphodius granarius	**Head Capsule Width**	
Life Stage	**Range**	**Mean ± SD**
Instar 1	0.7	
Instar 2	0.89 – 1.21	1.02 ± 0.069
Instar 3	1.3 - 1.78	1.53 ± 0.079

Figures 11 and 12 represent the instar stages of *A. spretulus* plotted on the calendar date of the respective year that the specimens were collected. Figures 13 and 14 represent the instar stages of *A. granarius* plotted on the calendar date that the specimens were collected. There were no grubs found before calendar date 142 (May 21) in either year. With the exception of three of each specie found on calendar 261 in 1992, no other *A. spretulus or A. granarius* grubs were found after 235 (August 21) in either year. In 1992 and 1993, the presence of both grub species occurred predominantly between calendar dates 184 and 205, a three week period. The *A. granarius* were mostly in third instar stages and the *A. spretulus* were in second and third instar stages. If grub damage from both *A. granarius* and *A. spretulus* is to be prevented using insecticides, timing of the application may be most beneficial during this period of species overlap.

Table 13 provides a breakdown of *A. spretulus* and *A. granarius* grub populations at each golf course sampled in 1992 and 1993. Tam O'Shanter Country Club had limited *A. spretulus* grubs in both 1992 and 1993, and no *A. granarius* in either year. At three

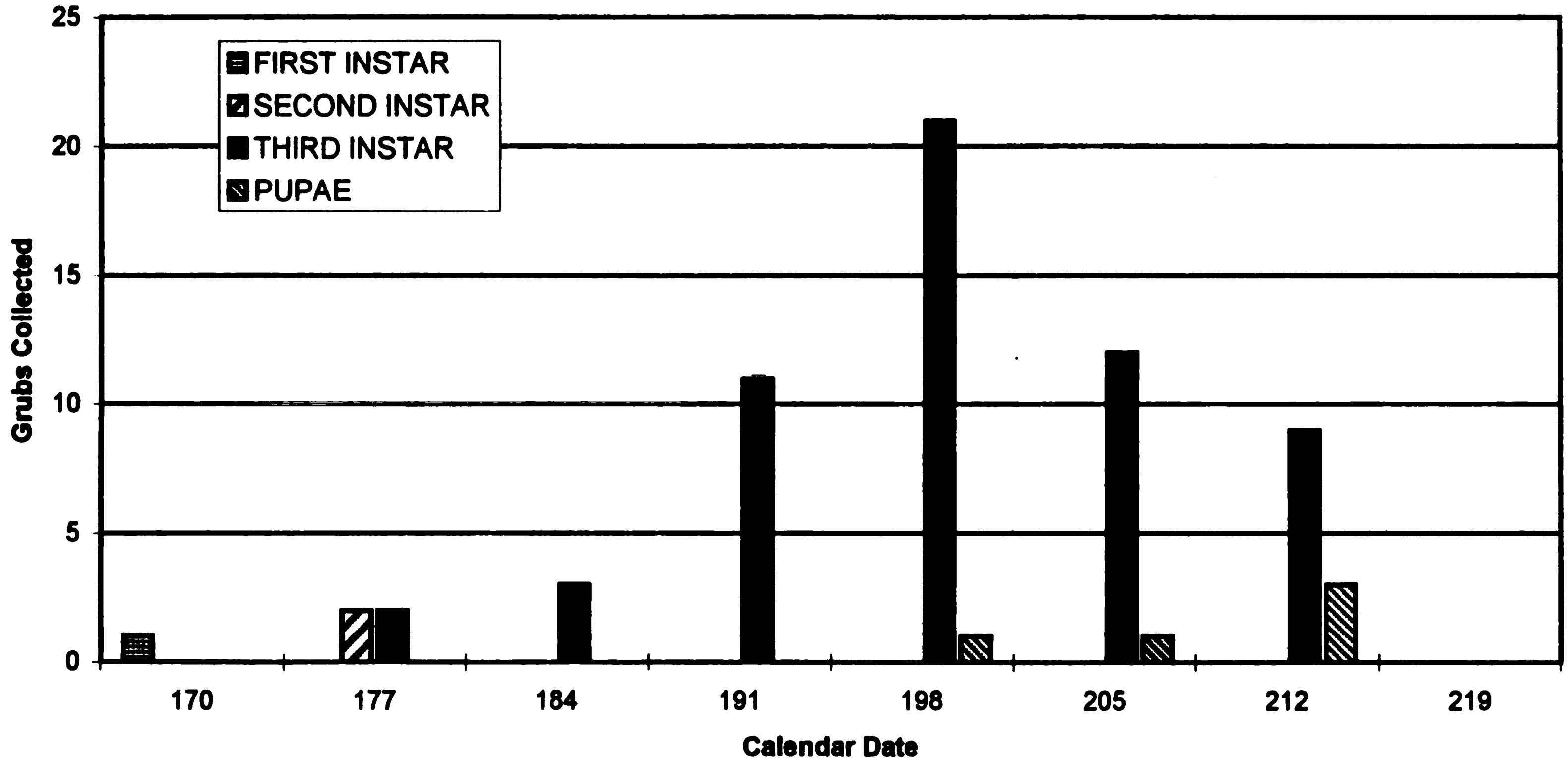

Figure 11. ***Ataenius spretulus*** **instars. 1992.**

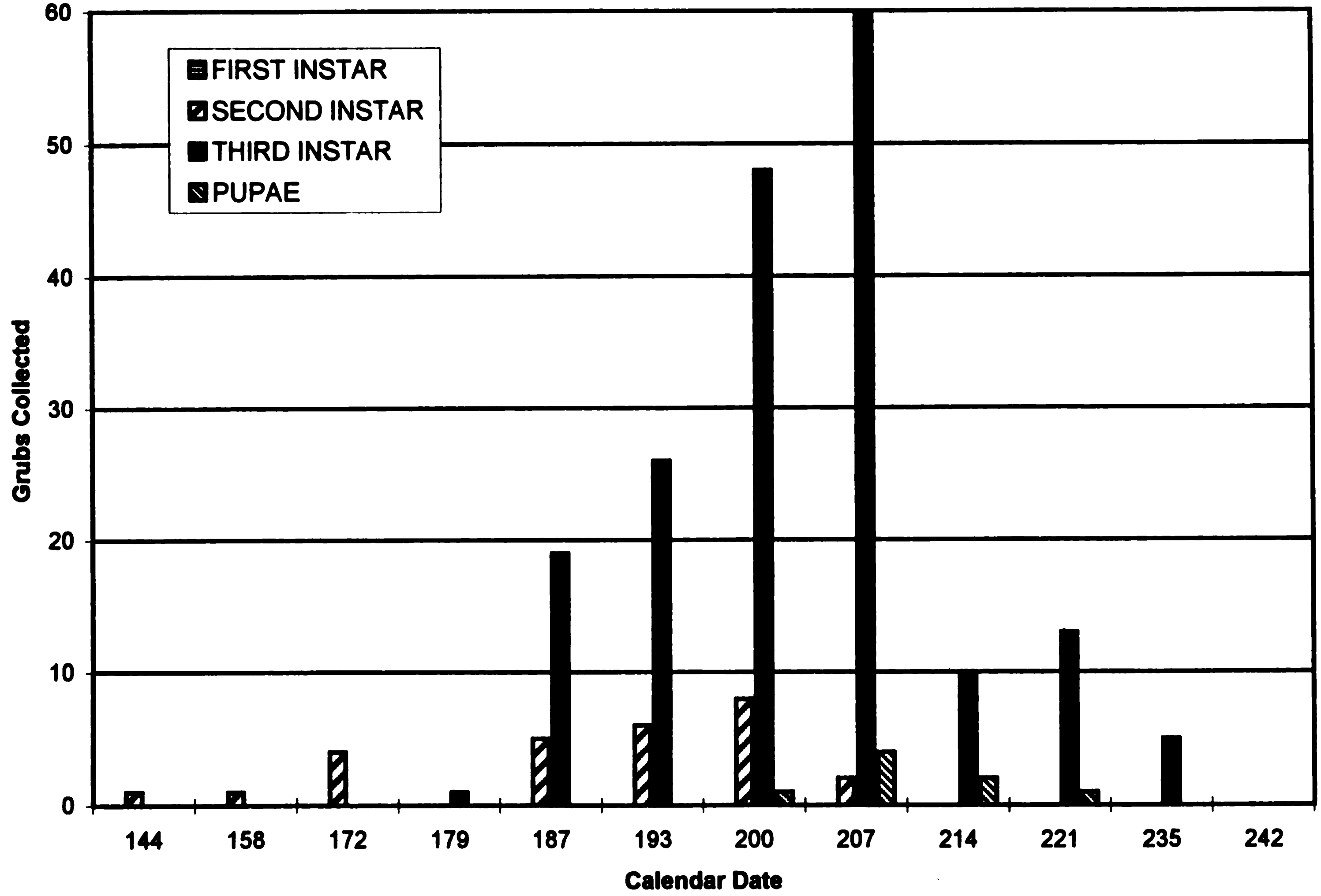

Figure 12. *Ataenius spretulus* Instars. 1993.

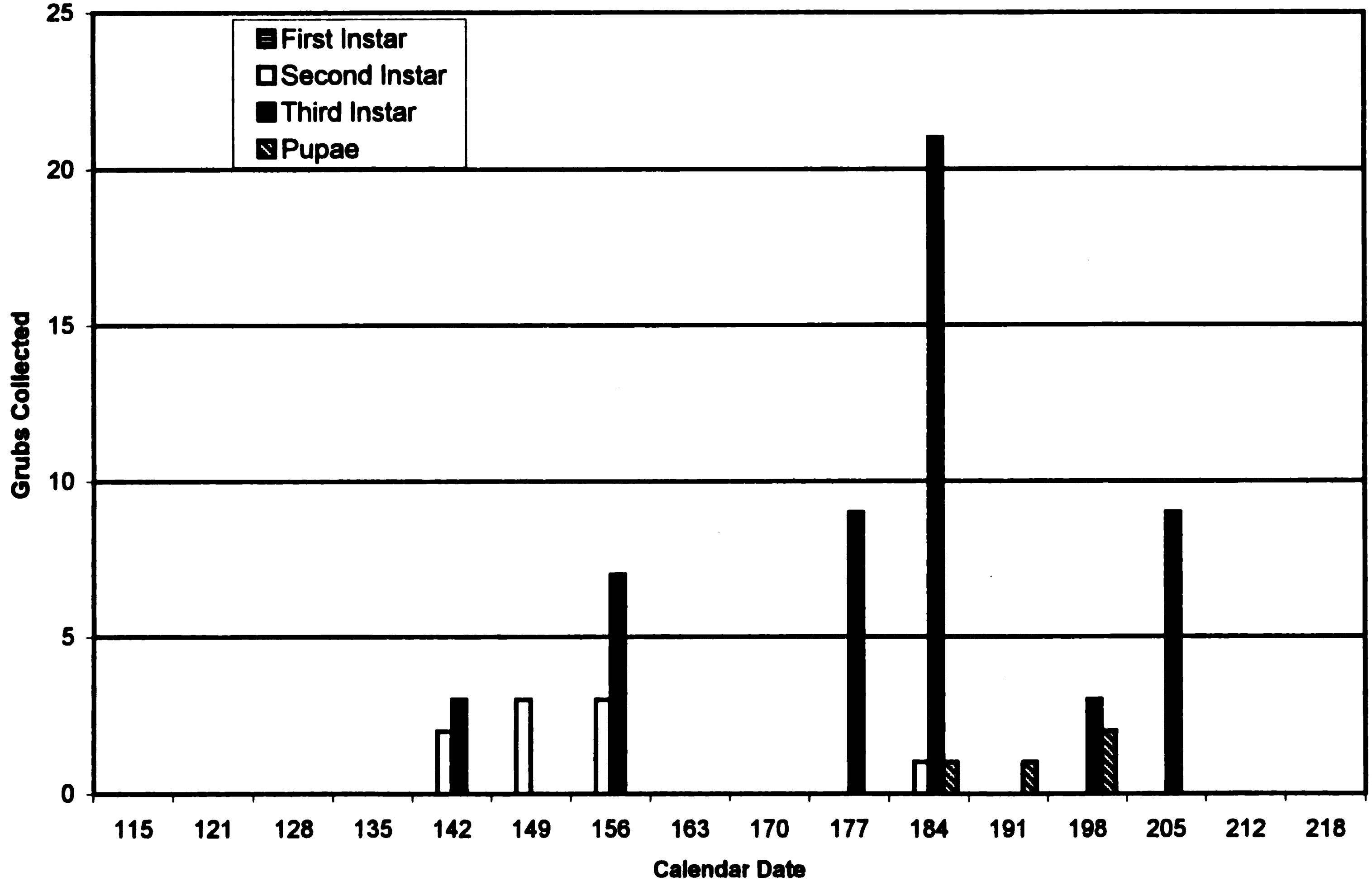

Figure 13. *Aphodius granarius* Instars. 1992.

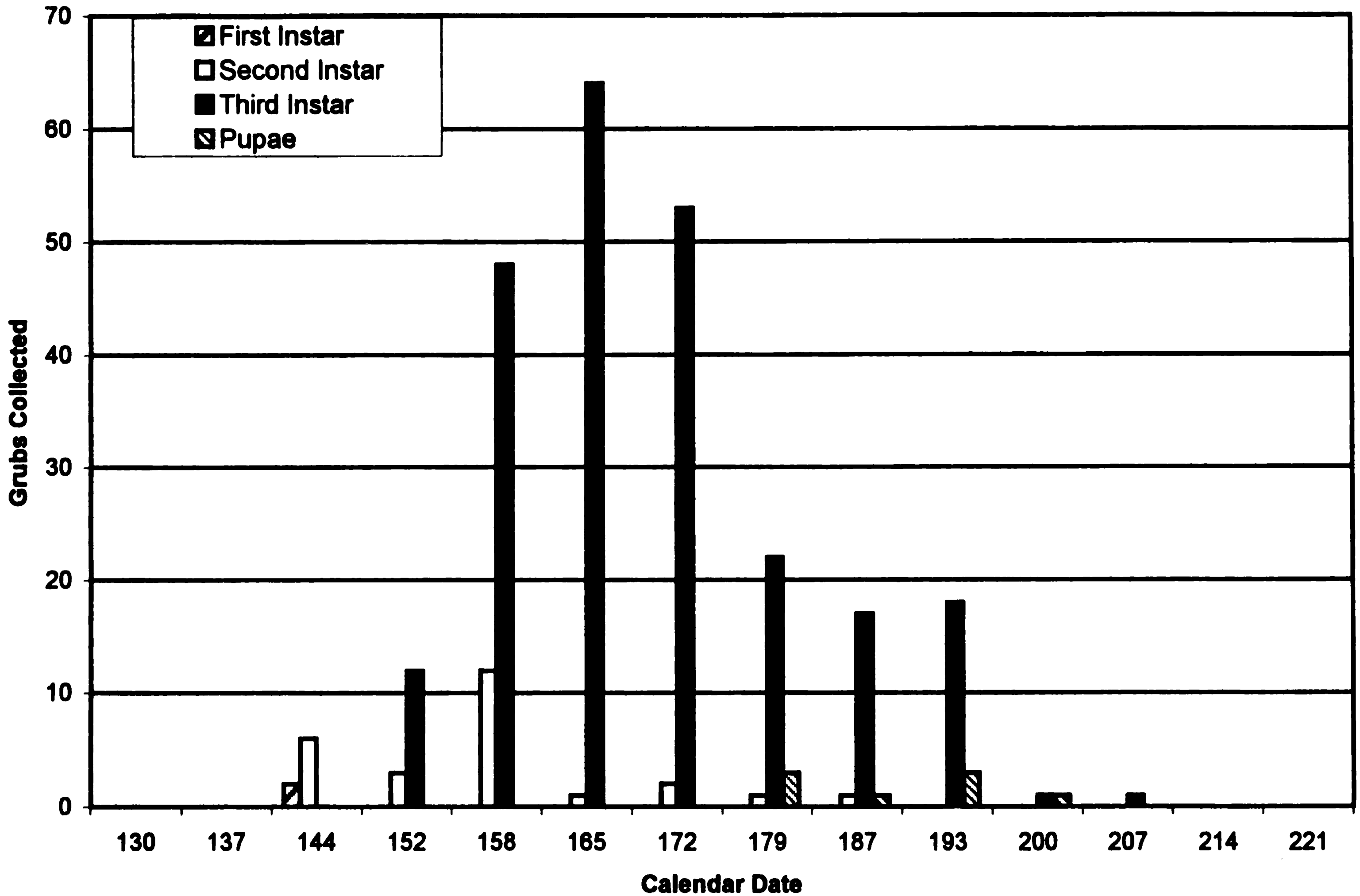

Figure 14. *Aphodius granarius* instars. 1993.

courses—Edgewood, Forest Lake, and Franklin Hills Country Clubs—the fraction of *A. spretulus* in the population increased from 1992 to 1993, although the *A. spretulus* numbers at Edgewood Country Club were very low (10) in 1993. At two courses—Oakland Hills and Orchard Lake Country Clubs—there was a large increase from 1992 to 1993 in the proportion of *A. granarius* compared to *A. spretulus*. At Oakland Hills Country Club, although the *A. granarius* increased from 46 to 88%, there was an overall 47% decrease in the total grub population between 1992 and 1993. The *A. granarius* population at Orchard Lake Country Club increased from 3 to 56% of the grub population from 1992 to 1993, yet the total grub population decreased 50% during the same period.

Table 13. Percent of *A. spretulus* and *A. granarius* in the populations sampled at six golf courses. 1992 and 1993.

Location	1992			1993		
		A. spretulus	*A. granarius*		*A. spretulus*	*A. granarius*
Country Club	**n**	**(%)**	**(%)**	**n**	**(%)**	**(%)**
Edgewood	52	83	17	10	100	0
Forest Lake	45	9	91	13	62	38
Tam O'Shanter	10	100	0	7	100	0
Oakland Hills	485	54	46	227	12	88
Orchard Lake	270	97	3	137	64	56
Franklin Hills	34	91	9	92	100	0

Ataenius spretulus and *Aphodius granarius* Larvae and Degree-Day Indexes

One objective associated with this project involved relating degree-days (DD) based on golf course air temperatures, soil temperatures at two depths, and regional DD data with the occurrences of *A. spretulus* and *A. granarius* larvae. Air based DD are the standard indexes used by turfgrass and ornamental plant managers. Yet, since *A. spretulus* and *A. granarius* spend a large portion of their lives in the soil environment, it seemed likely that a soil based DD index may be a more precise measure of the insects' activity. Figures 15 through 18 represent the *A. granarius* and *A. spretulus* grub occurrence in 1992 or 1993 plotted with either the golf course air and soil DD, or the golf course air and regional DD indexes.

APHODIUS GRANARIUS

Figures 15 and 16 show that *A. granarius* larvae were first found on calendar date 142, in 1992. Figures 17 and 18 show that the first *A. granarius* and *A. spretulus* larvae were found on the same calendar date, 144, in 1993. On the respective calendar dates of the first *A. granarius* grub recovery, the golf course DD were 121 for air in 1992 and 140 in 1993; 111 for soil 2.5 cm in 1992 and 143 in 1993; and 108 for soil 5.0 cm in 1992 and 134 in 1993.

The greatest number of *A. granarius* grubs were collected in 1992 on calendar date 174, and on calendar date 165 in 1993. Note that in 1992, 174 was the first date that the three golf courses with the larger grub populations were sampled that year, which means the peak numbers of *A. granarius* larvae may have been missed. Sampling at these courses began earlier in the season in 1993 to avoid missing early *A. granarius* grub activity. On the peak *A. granarius* grub date 174, 1992, the golf course DD were 319 air; 371 soil 2.5 cm; and 380 soil 5.0 cm (Figure 15). The peak *A. granarius* grub collection date 165, 1993 correlated with golf course DD of: 260 for air; 294 for soil 2.5 cm; and 279 for soil 5.0 cm (Figure 17). In both years the soil DD had exceeded the total air DD at the time of peak *A. granarius* larvae collection.

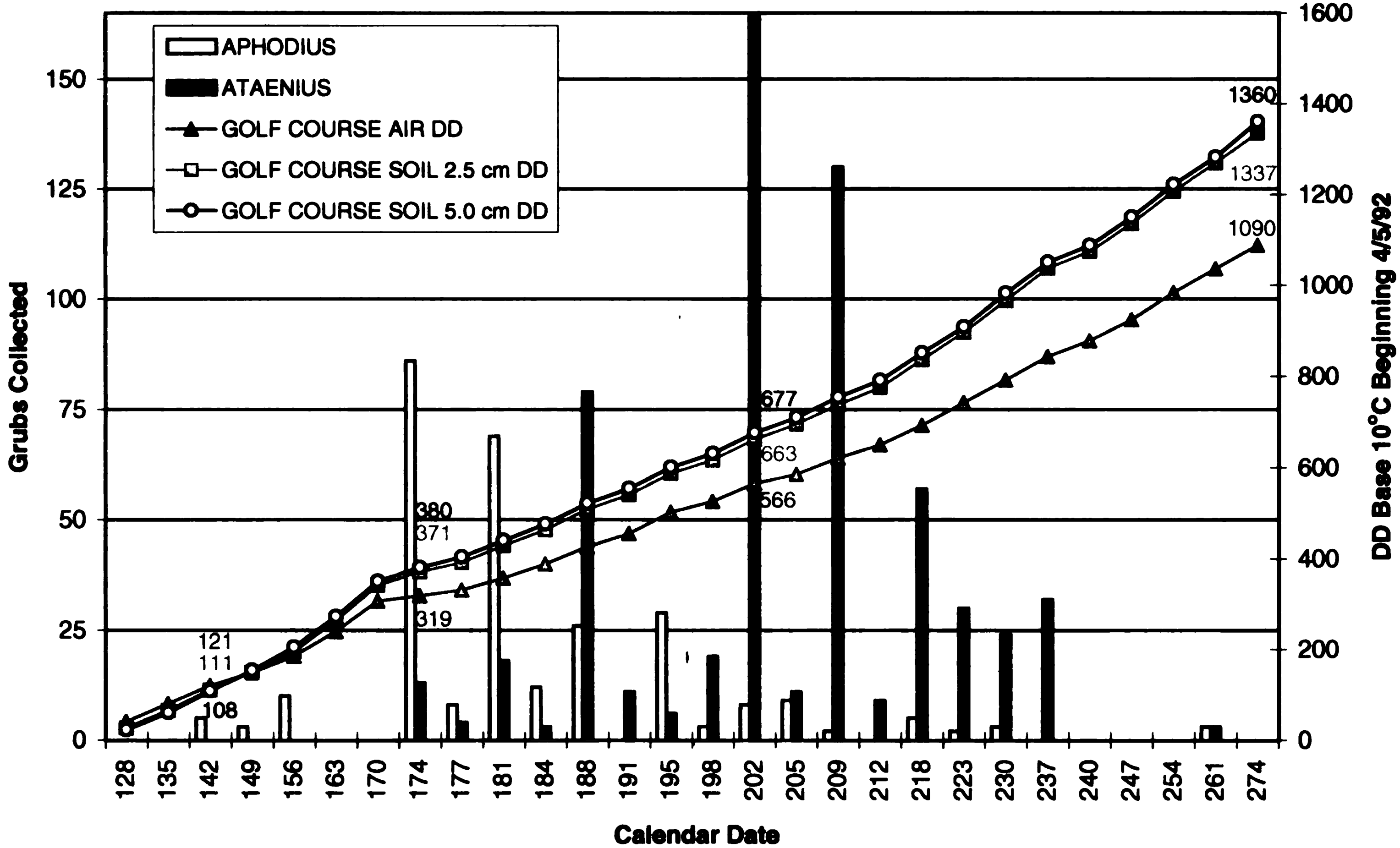

Figure 15. *Ataenius spretulus* and *Aphodius granarius* grubs, golf course air and soil DD. 1992.

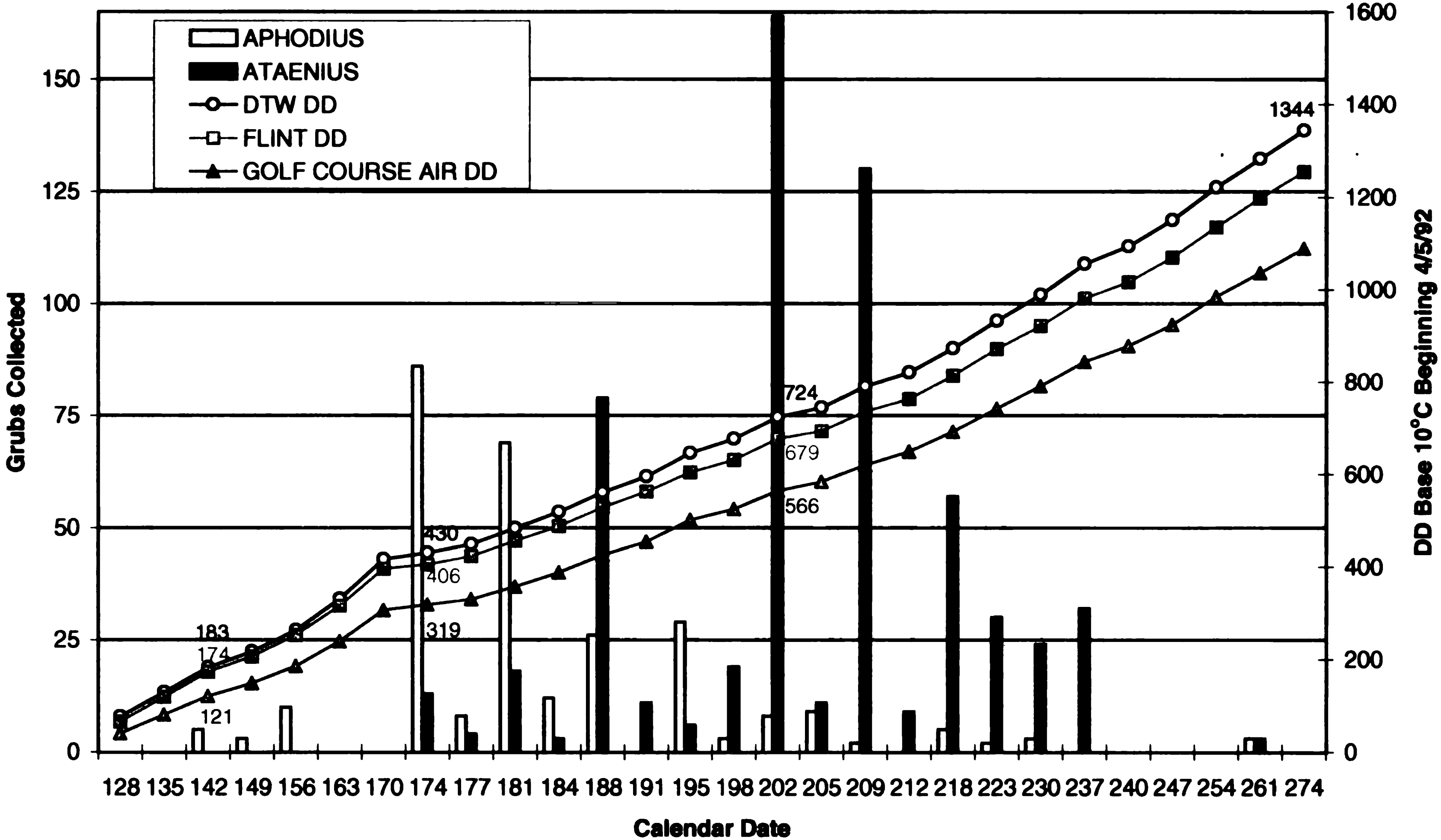

Figure 16. ***Ataenius spretulus*** **and** ***Aphodius granarius*** **grubs, regional and golf course air DD. 1992.**

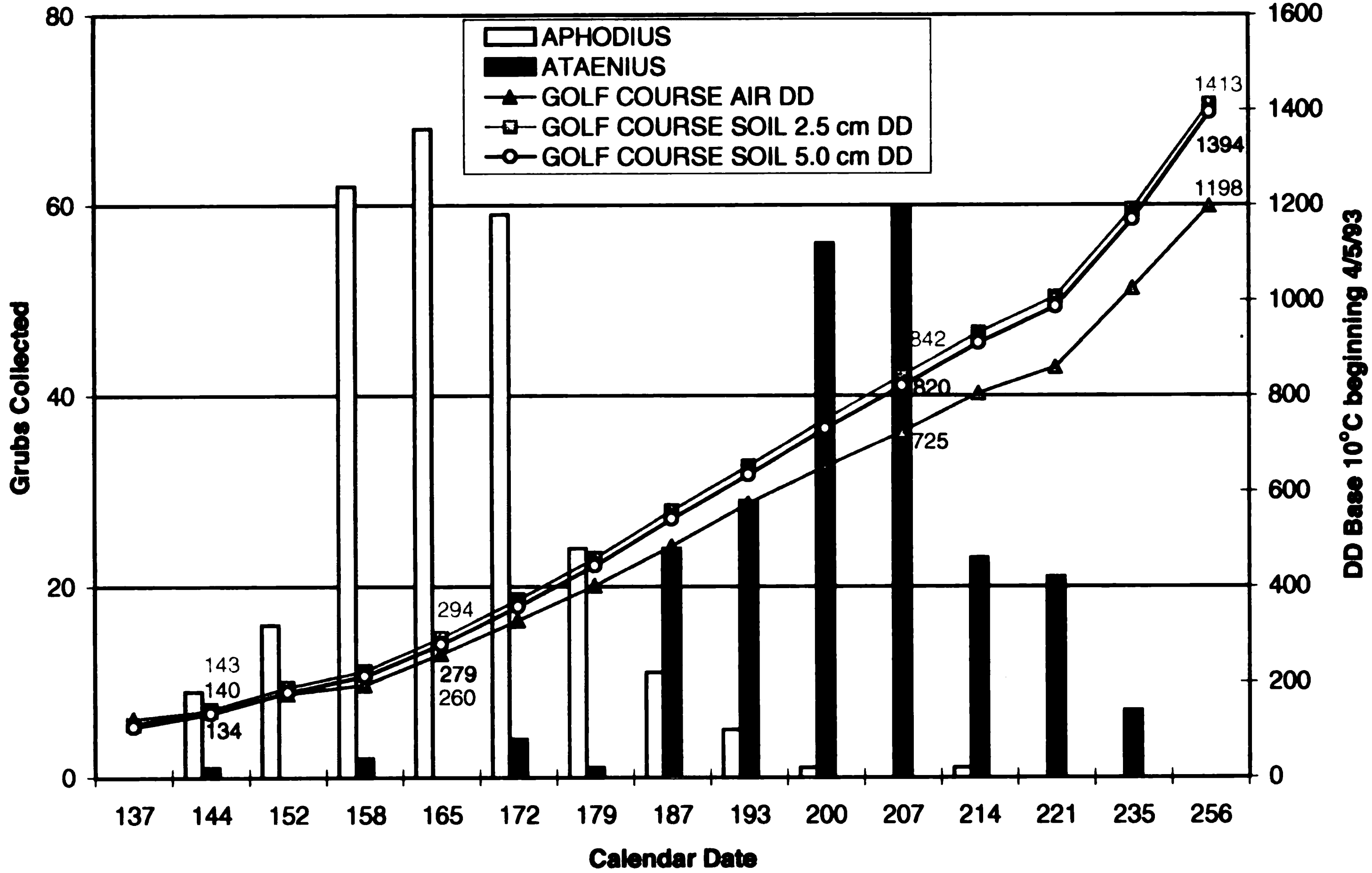

Figure 17. *Ataenius spretulus* and *Aphodius granarius* grubs, golf course air and soil DD. 1993.

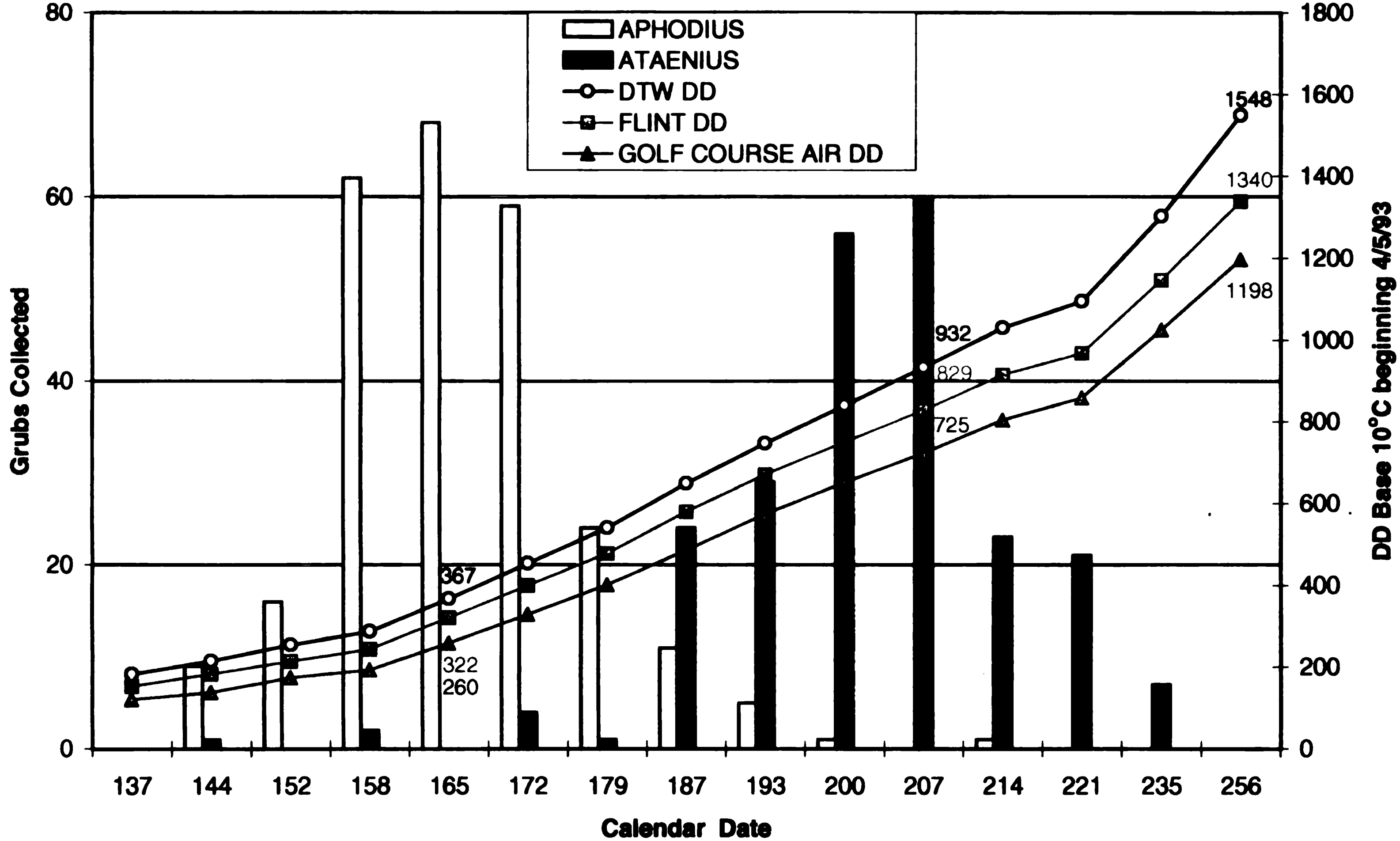

Figure 18. ***Ataenius spretulus*** **and** ***Aphodius granarius*** **grubs, regional and golf course air DD. 1993.**

Regional DD BE base 10°C beginning April 5, 1992 were plotted with grub sampling data and golf course air DD in Figure 16 (Baskerville and Emin, 1968). On the date of peak *A. granarius* collection, which was also the first date of locating *A. spretulus* larvae in 1992, the regional DD were 406 at Flint and 430 at DTW. The 1992 regional DD totals were greater than the golf course air and both soil DD values at that time. The 1993 regional DD are plotted with *A. granarius* and *A. spretulus* grub counts and golf course air DD and are seen in Figure 18. The 1993 regional DD on the date of peak *A. granarius* grub collection were 322 at Flint and 367 at DTW.

By comparing the incidence of *A. granarius* larvae to calendar dates and DD of both years, some generalizations may be made. In Table 14, the dates of the two largest collections of *A. granarius* for both 1992 and 1993 are listed with the corresponding DD totals. The period of the most grub activity occurred eight days earlier in 1993 (dates 165, 172) than in 1992 (dates 174, 181; leap year). Including both years, 15 calendar days represent the period of the most *A. granarius* grub activity (June 14-29).

As seen in Table 14, including both years' observations, the golf course air DD ranged from 260 to 358 during the periods of greatest *A. granarius* grub activity. Air DD data were the least variable DD between years (98 DD). Between 1992 and 1993, the soil 2.5 cm DD ranged 294-429 (135 DD) and soil 5.0 cm DD ranged 279-439 (160 DD) during the periods of greatest grub activity. The regional DD ranges were, Flint 322- 457 (135 DD); and DTW 367-484 (117 DD). The DD corresponding to the greatest grub activity in 1992 were greater than the 1993 DD totals for the same activity.

Table 14. Peak *Aphodius granarius* grub collection dates and corresponding DD. 1992 and 1993.

	1992	1992	1993	1993
Number of Grubs	86	69	68	59
Calendar Date	174*	181 **	165*	172 **
Air DD	319	358	260	330
Soil 2.5 cm DD	371	429	294	374
Soil 5.0 cm DD	380	439	279	358
Flint DD	406	457	322	401
DTW DD	430	484	367	453

*, ** Date of the largest number of grubs, and second largest number of grubs collected, respectively.
DD base 10°C beginning April 5 of the respective year.

Based on the DD and *A. granarius* grub observations made in 1992 and 1993, there appears to be no advantage in monitoring soil temperatures rather than air temperatures for establishing DD indexes to predict *A. granarius* development. Across the two years, the soil DD ranges (135 and 160, respectively) were 30% more variable than the air DD (range of 98) at the time of peak activity. Based on these two years of observations, and the variability in DD ranges that relate with *A. granarius* grub activity, it is not possible to specify a precise air or soil-based DD for peak grub activity.

Since golf course air and Flint airport temperatures are not statistically different (Table 6), at best, the golf course air DD base 10°C beginning April 5 range of 260-358, or Flint DD BE base 10°C range 322-457 could be used as a guideline for determining peak *A. granarius* grub activity. Turfgrass managers would be advised to begin scouting for *A. granarius* grubs the last week of May and the first week of June, calendar dates 144-151, and 152-159, respectively, with potential peak activity occurring between calendar dates 165-180. Where possible, the use of site-specific data compared to local grub activity over a period of time will help turf managers define periods of *A. granarius* grub activity on their sites.

ATAENIUS SPRETULUS

In 1992, the first *A. spretulus* larvae were found on calendar date 174 (Figures 15 and 16). The golf course DD were, 319 for air, 371 for soil 2.5 cm, and 380 for soil 5.0 cm. Figures 17 and 18 show that the first 1993 *A. spretulus* larvae were found on calendar date 144 yet, grub numbers did not increase until calendar 172, and then more significantly by 187.

Peak *A. spretulus* grub collection occurred on calendar date 202 in 1992 and on 207 in 1993. The golf course DD for those dates were: 566 air in 1992 and 725 in 1993; 663 soil 2.5 cm in 1992 and 842 in 1993; and 677 soil 5.0 cm in 1992 and 820 in 1993 (Figures 15 and 17).

As illustrated in Figures 15 through 18, the *A. spretulus* larvae peak and pupate after the *A. granarius* larvae population. This may be a deliberate effort on the part of the species to avoid competition for the same habitat and food source. As was seen in a sheep pasture (Wilson, 1932), *A. granarius* conveniently chose dung piles for ovipositing only after they had dried enough to attract the beetles, and the fly larvae—which had been feeding and developing in the dung hills—had already pupated.

In 1992 and 1993 there was a two-week period when the grubs of both species were present, calendar dates 173 -187. During this period a small portion of second instar *A. granarius* were present with mostly third instar grubs and pupae pulled from samples. The *A. spretulus* sampled during this time were second and third instar grubs.

The regional DD, golf course air DD, and grubs are plotted together for 1992 and 1993 in Figures 16 and 18, respectively. On the peak *A. spretulus* collection dates 202 and 207, the regional DD were 679 in 1992 for Flint and 829 in 1993; and 724 in 1992 for DTW and 932 in 1993. The regional DD associated with peak *A. spretulus* in 1992 were approximately 40% greater than the total DD at the time of peak *A. granarius* grubs. In 1993, the regional DD associated with peak *A. spretulus* were almost three times greater than the DD totals corresponding to peak *A. granarius* grub activity.

Presented in Table 15 are the DD data for 1992 and 1993 during the period of the greatest *A. spretulus* activity. The largest and second largest grub collections occurred during the same calendar week each year, e.g., 202-209 in 1992, and 200-207 in 1993 (July 19-26). Sampling error may have contributed to the peak numbers occurring on opposite weeks between 1992 and 1993.

The golf course air DD ranged from 566 to 725 during the periods of greatest *A. spretulus* grub activity in 1992 and 1993 (Table 15). The golf course air data were more variable between years (159 DD) than the soil 5.0 cm or Flint DD. The soil 2.5 cm DD were 663-842 (179 DD), and soil 5.0 cm DD were 677-820 (143 DD) during the periods of greatest grub activity. The regional DD ranges were 679-829 at Flint (150 DD); and 724-932 at DTW (208 DD). With the exception of soil 5.0 cm, all of the DD values corresponding to the greatest grub activity in 1992 were lower than the 1993 DD totals for the same activity.

Table 15. Peak *Ataenius spretulus* grub collection dates and corresponding DD. 1992 and 1993.

	1992	1992	1993	1993
Number of Grubs	164	130	60	56
Calendar Date	202*	209**	207*	200**
Air DD	566	622	725	652
Soil 2.5 cm DD	663	739	842	751
Soil 5.0 cm DD	677	754	820	730
Flint DD	679	738	829	751
DTW DD	724	791	932	840

*, ** Date of the largest number of grubs, and second largest number of grubs collected, respectively.
DD base 10°C beginning April 5 of the respective year.

Southeast Lower Michigan had two climatologically different years during this study. Each month during the April – September, 1992 period temperatures were consistently below normal while the same six-month period in 1993 had close to normal or above normal temperatures (NOAA, 1992 and 1993). With this difference it was expected that the activity of *A. spretulus* and time of grub appearance would be variable between years. In these two years the *A. spretulus* grub activity peaked during the same calendar week. Looking closer at the temperatures for these two years, the greatest deviation from normal temperatures, and therefore DD accumulations, occurred in July and August in 1992 (Table 16). In the early part of the season, calendar 95-207, when the adult beetles were active and ovipositing, eggs were hatching and grubs developing, there was little difference in temperatures between years. Table 16 provides the mean monthly temperatures and the golf course air DD. Mean temperatures for April, May, and June were similar between years while larger temperature and DD accumulation differences arose in July and August.

Table 16. Mean monthly temperatures for Southeast Lower Michigan and monthly golf course air DD. 1992 and 1993.

Month	1992 Mean °C	1993 Mean °C	1992 DD Range	1993 DD Range
April	7.3	8.0	0-23	0-29
May	14.3	13.3	23-160	29-172
June	18.0	19.1	160-379	172-416
July	20.2	23.4	379-660	416-787
August	19.2	22.6	660-904	787-1124
September	16.6	14.9	904-1090	1124-1254

The DD indexes related to the *A. spretulus* grub activity resulted in fairly large ranges. It would be difficult to associate these ranges with a specific period of time that may predict actual peak grub activity. For instance, the golf course air DD range associated with the greatest *A. spretulus* activity in this study spans 179 DD (566 - 725). In early July, of 1992 and 1993, heat units were accumulating at approximately 58 DD, and 70 DD per week, respectively. Thus, an index spanning 179 DD base 10°C could represent a 2.5 to 3 week period. A three-week time frame may not be practical to a turf manager needing to know the best timing for control strategies. Contact insecticides with short residuals have a narrow window of control activity and must be applied when the grubs are close to the soil surface and actively feeding. Newer insecticides now available on the market have longer residuals and would be useful tools for managing grubs that may hatch and develop over several weeks.

Certain ornamental and Christmas tree pests have DD base 10°C ranges that span as little as 18 (gypsy moth first larvae) and as many as 112 thermal units (spruce bud scale, first crawlers) and are practical indexes for plant managers (McCullough, 1997). Since the DD ranges observed in this study are fairly large, 150 and greater, their use, at best would serve only as an initial guide to monitor for *A. spretulus* activity. The golf course air DD range of 566-725, or Flint 679-829 DD correlated with peak *A. spretulus* grub activity during this study. Further observations of the *A. spretulus* in relationship to DD are needed to possibly refine the ranges that might be used to represent the various stages of development and activity. Based on the information gathered during this study, calendar dates are a more precise tool for predicting *A. spretulus* than air or soil based DD.

This conclusion, that calendar dates are a more precise tool for predicting *A. spretulus* than air or soil based DD held true for first generation *A. spretulus* in a recent season characterized by above normal temperatures. Based on personal scouting activities in 1998 at golf courses within 2-3 km of the sites sampled during this study, a second generation of *Ataenius spretulus* occurred. Based on field records, adult *A. spretulus* were present on greens May 4 and 7 and grubs were found causing damage in fairways on July 20, 1998. Adult *A. spretulus* were also noted on greens August 17. In addition, grubs, pupae and callow adults were found in fairways September 15, 1998 indicating the completion of at least a partial second generation.

Preliminary climatological data indicate that the period January-October 1998 was the second warmest such period since 1895 for the contiguous United States. The East North Central U.S. normal temperature is 26.1°C and 1998 values for January-October were 28.3°C (National Climatic Data Center, 1998). Again, even with above normal seasonal temperatures, *A. spretulus* grub activity took place the third week of July, consistent with both cool (1992), and closer to normal (1993) climatological events. The difference in 1998 was that a complete second generation occurred. This would suggest that heat is a factor influencing the potential for a second generation of *A.*

spretulus in Michigan, although the connection between heat units, other environmental factors and the biological development of development of *A. spretulus* is more complex than this study was designed to detect.

APPENDICES A, B, AND C

APPENDIX A

Regression values used for estimating missing temperature data.

Table A.1 Values used to estimate missing data for Edgewood 1992.

Month	Variable	Site Comparison	R squared	X coefficient
May 22-28	Soil 2.5 cm	Forest Lake	.99	0.058
	Soil 5.0 cm	Tam O'Shanter	.88	0.918

Table A.2 Values used to estimate missing data for Tam O'Shanter 1992.

Month	Variable	Site Comparison	R squared	X coefficient
April 5-9	Air	Forest Lake	.95	1.018
	Soil 5.0 cm	Edgewood	.93	0.912
May 7-13	Air	Forest Lake	.94	2.056
	Soil 2.5 cm	Edgewood	.89	0.873
June 25-27	Air	Forest Lake	.95	1.007
	Soil 5.0 cm	Edgewood	.82	0.933

Table A.3 Values used to estimate missing data for Edgewood 1993.

Month	Variable	Site Comparison	R squared	X coefficient
April 22-29	Air	Forest Lake	.92	1.016
	Soil 2.5 cm	Forest Lake	.98	1.302
	Soil 5.0 cm	Forest Lake	.99	1.367
May 17	Air	Hancock Center	.85	0.889
	Soil 2.5 cm	Hancock Center	.80	1.009
	Soil 5.0 cm	Hancock Center	.85	1.032
June 21	Air	Forest Lake	.95	1.031
	Soil 2.5 cm	Forest Lake	.97	0.987
	Soil 5.0 cm	Forest Lake	.95	1.004
July 12-18	Air	Forest Lake	.93	0.986
	Soil 2.5 cm	Forest Lake	.95	0.951
	Soil 5.0	Forest Lake	.96	0.971

Appendix A. (cont'd)

Table A.4 Values used to estimate missing data for Tam O'Shanter 1993.

Month	Variable	Site Comparison	R squared	X coefficient
May 13-18	Air	Edgewood	.97	0.972
	Soil 2.5 cm	Edgewood	.90	0.911
	Soil 5.0 cm	Edgewood	.86	1.057
July 12-18	Air	Forest Lake	.93	0.961
	Soil 2.5 cm	Forest Lake	.91	0.738
	Soil 5.0	Forest Lake	.94	0.857
August 16-18	Air	Edgewood	.96	0.971
	Soil 2.5 cm	Edgewood	.78	0.614
	Soil 5.0 cm	Edgewood	.82	0.732
September 1-6	Air	Edgewood	.95	0.924
	Soil 2.5 cm	Edgewood	.86	0.719
	Soil 5.0 cm	Edgewood	.88	0.748

Table A.5 Values used to estimate missing data for Forest Lake 1993.

Month	Variable	Site Comparison	R squared	X coefficient
May 13-18	Air	Edgewood	.94	0.961
	Soil 2.5 cm	Edgewood	.93	0.858
	Soil 5.0 cm	Edgewood	.93	0.871
August 10-15	Air	Edgewood	.93	0.96
	Soil 2.5 cm	Edgewood	.95	1.127
	Soil 5.0	Edgewood	.95	1.089

APPENDIX B

FORTRAN program for calculating degree-days base 10°C.

Table B.1. FORTRAN program.

```
      REAL TDB,X2,X4,RAIN,ST1,ST2,SYS,PRN
      REAL GDD10,GDDAY,GDWEEK,TDW
      REAL GDDAYST,GDDAYST2,GDWEEKST,GDWEEKST2
      INTEGER MM,DD,YY,TIME,RH,WS,WD,DEW
      CHARACTER*80 INPUT1,OUTPUT1
      WRITE(*,*) 'ENTER INPUT FILE NAME '
      READ(*,380) INPUT1
      WRITE(*,*) 'ENTER OUTPUT FILE NAME '
      READ(*,380) OUTPUT1
380   FORMAT(A)
      OPEN(1,FILE=INPUT1,STATUS='UNKNOWN')
      OPEN(2,FILE=OUTPUT1,STATUS='UNKNOWN')
      BASE=10.
      GDDAY=0.0
      GDWEEK=0.0
      GDDAYST=0.0
      GDDAYST2=0.0
      GDWEEKST=0.0
      GDWEKST2=0.0
         DO 1000 I=1,200
            DO 2000 J=1,24
      READ(1,*,END=23) MM,DD,YY,TIME,TDB,ST1,ST2
      GDD50=(TDB-BASE)*0.0416667
      IF(GDD10.LT.0.) GDD10=0.0
      GDDAY=GDDAY+GDD10
      GDDST=(ST1-BASE)*0.0416667
      IF(GDDST.LT.0.) GDDST=0.0
      GDDAYST=GDDAYST+GDDST
      GDDST2=(ST2-BASE)*0.0416667
      IF(GDDST2.LT.0.) GDDST2=0.0
      GDDAYST2=GDDAYST2+GDDST2
2000  CONTINUE
      PRINT*,'DAILY GDD TOTAL FOR ',DD,MM,YY,' IS ',GDDAY
      PRINT*,'TOTAL FOR SOIL LEVEL 1 IS ',GDDAYST
      PRINT*,'TOTAL FOR SOIL LEVEL 2 IS ',GDDAYST2
      GDWEEK=GDWEEK+GDDAY
      GDWEEKST=GDWEEKST+GDDAYST
      GDWEKST2=GDWEKST2+GDDAYST2
      WRITE(2,10)
```

Appendix B. (cont'd).

```
      DD,MM,YY,GDDAY,GDWEEK,GDDAYST,GDWEEKST,
      $GDDAYST2,GDWEKST2
 10   FORMAT(I3,I3,I3,F5.0,F7.0,F5.0,F7.0,F5.0,F7.0)
      GDDAY=0.0
      GDDAYST=0.0
      GDDAYST2=0.0
 1000 CONTINUE
 23   PRINT*,'SEASONAL GDD TOTAL IS ',GDWEEK
      PRINT*,'SEASONAL TOTAL AT SOIL LEVEL 1 IS ',GDWEEKST
      PRINT*,'SEASONAL TOTAL AT SOIL LEVEL 2 IS ',GDWEKST2
C     WRITE(2,20) GDWEEK
C 20  FORMAT('SEASONAL GDD TOTAL (AIR) IS ',F4.0)
C     WRITE(2,21) GDWEEKST
C 21  FORMAT('SEASONAL TOTAL AT SOIL LEVEL 1 = ',F4.0)
C     WRITE(2,22) GDWEKST2
C 22  FORMAT('SEASONAL TOTAL AT SOIL LEVEL 2 = ',F4.0)
      STOP
END
```

APPENDIX C

Soil analyses from areas sampled for *A. spretulus* and *A. granarius* larvae at three golf courses.

Table C.1 Soil analyses from three golf courses. 1992.

1992	Edgewood	Forest Lake	Tam O'Shanter
Chemical Quality			
Soil pH	7.1	6.2	7.7
Phosphorus	286 kg/ha	269 kg/ha	47 kg/ha
Potassium	122 kg/ha	245 kg/ha	273 kg/ha
Calcium	1622 kg/ha	2075 kg/ha	5276 kg/ha
Magnesium	188 kg/ha	358 kg/ha	657 kg/ha
CEC	4.5 me/100 g	6.2 me/100 g	14.5 me/100 g
Particle Size			
Sand	95.6%	82.6%	61.1%
Silt	1.0%	12.0%	20.0%
Clay	3.4%	5.4%	18.9%
Texture class	sand	loamy sand	sandy loam

Table C.2 Soil analyses from three golf courses. 1993.

1993	Edgewood	Forest Lake	Tam O'Shanter
Chemical Quality			
Soil pH	7.4	6.3	7.0
Phosphorus	304 kg/ha	277 kg/ha	87 kg/ha
Potassium	283 kg/ha	358 kg/ha	226 kg/ha
Calcium	2987 kg/ha	2049 kg/ha	2901 kg/ha
Magnesium	430 kg/ha	412 kg/ha	475 kg/ha
CEC	8.6 me/100 g	8.9 me/100 g	8.5 me/100 g
Particle Size			
Sand	72.6%	76.6%	68.6%
Silt	12.7%	12.7%	18.7%
Clay	14.7%	10.7%	12.7%
Texture class	sand	sandy loam	sandy loam

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