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Mowing Height Influences *Listronotus maculicollis* (Coleoptera: Curculionidae) Oviposition Behavior and Mechanical Removal From Golf Course Putting Greens, but Not Larval Development

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Abstract

The annual bluegrass weevil, *Listronotus maculicollis* (Kirby), is a highly destructive pest of golf course turfgrass in eastern North America. Previous research has demonstrated that females prefer to oviposit within short-mown turfgrasses (<1.25 cm), and these offspring have improved fitness traits compared with larvae developing in higher-mowed turf. However, damage to putting green turf (<3.55 mm) is rarely reported. We investigated whether this phenomenon was due to adult removal through mowing or an inability of larvae to develop within a shortened plant. Greenhouse studies revealed that between 26% and 38% of adults were removed when turf was mowed at 2.54 mm (0.100 in), but the effect diminished with increasing mowing heights. The majority of adults survived mowing, indicating a potential for adults to reinvade turf stands adjacent to areas where grass clippings are discarded. Females oviposited in all mowing height treatments in laboratory and field experiments. However, behavior was influenced by plant height, as significantly fewer eggs were placed inside of the turfgrass stem at the lowest mowing height. Larval development was not affected by egg placement or turf height, and significant numbers of larvae were capable of developing to damaging stages (fourth- and fifth-instar larvae) in all treatments. Our findings suggest that *L. maculicollis* poses a threat to putting green-height turf, but the probability of damage occurring and need for insecticide applications may be lessened on low-mown surfaces. Future studies are needed to determine factors that influence *L. maculicollis* movement within the turfgrass canopy to optimize mechanical control.

Key words: annual bluegrass weevil, *Listronotus maculicollis*, mechanical control, mowing, turfgrass

The annual bluegrass weevil, *Listronotus maculicollis* (Kirby), is considered the most devastating turfgrass insect pest of short-mown turf in the northeastern and mid-Atlantic United States and the southeastern provinces of Canada (Vittum et al. 1999, McGraw and Koppenhöfer 2007). In spring, flightless adults walk from overwintering sites (e.g., leaf litter, tall grass) onto short-mown turfgrass areas to feed and mate (Diaz and Peck 2007). The female will find a suitable host, chew a notch in the stem of the plant, and insert eggs into the stem or under the leaf sheath (Vittum 1980). Larvae are stem borers for the first three instars, though they may exit the plant to attack a new host to complete development. Eventually, the larva exits the stem of the plant to feed externally on the crown (apical meristem) during the fourth and fifth instars. These stages will often cause irreparable damage to the portion of the plant that gives rise to new growth. Voltinism of populations varies across the region, from one generation per year in Quebec (Simard et al. 2007) to as many as three in the southern regions (Virginia to North Carolina) of the weevil's distribution (Vittum et al. 1999). However, emerging overwintering adult populations are denser than subsequent generations in all locations, and the resulting damage in spring from first-generation late-instar larval feeding is usually most severe (Vittum et al. 1999).

Damage is particularly noticeable in short-mown (<1.25 cm) turfgrass stands with high percentages of annual bluegrass (*Poa annua* L.). Choice and no-choice assays have shown that females prefer to oviposit in short-mown (1.27 cm) turfgrasses compared with higher heights-of-cut (2.54 cm), and larvae gain more weight and develop faster in *P. annua* compared with other turfgrass species (Rothwell 2003, Kostromytska and Koppenhöfer 2014). However, reports of damage to creeping bentgrass (*Agrostis stolonifera* L.) have become more common, especially as the insect expands its distribution into new regions where *P. annua* is less prevalent. Both turfgrass species are commonly found in the areas on the golf course that are most important to the playing of the game (e.g., tee boxes, fairways, collars, and putting greens). Therefore, synthetic insecticides (contact insecticides for adults, and contact and systemic insecticides for larvae) are often applied sequentially throughout the growing season, from spring through summer, to prevent larval damage. A recent survey estimates that turfgrass managers make an average of four insecticide applications per season to control *L. maculicollis*, and that ~20% make six or more applications (McGraw and Koppenhöfer 2017). The overuse of broad-spectrum, preventive adulticides has resulted in resistance to pyrethroids, and in some *L. maculicollis* populations, a decrease in susceptibility to several unrelated classes of insecticides (Cowles et al. 2008, Ramoutar et al. 2009). The recent increase in prevalence of insecticide-resistant *L. maculicollis* populations has resulted in an urgent need to develop alternative management tactics.

Although chemical controls are typically applied to most, if not all turf areas mowed <1.25 cm, only 26% of golf course superintendents report observing *L. maculicollis* larval feeding in putting greens, compared with 58% in collars (the turf immediately bordering the putting green) and 69% in fairways (McGraw and Koppenhöfer 2017). Greens are typically maintained between 2.25–3.8 mm (0.100–0.150 in), frequently topdressed (the incorporation of fine sand particles into the canopy and thatch layer), fertilized, and treated with fungicides. It is common for damage to appear on a collar but not within the adjacent putting surface, despite both areas receiving the same chemical and cultural inputs with the exception of mowing height and frequency. Putting greens are mowed daily to maintain turf uniformity and density, typically six to seven times per week throughout the growing season. Collars are maintained between 0.5 (0.200 in) and 1 cm (0.400 in) and are mowed three to five times per week. These differences would suggest that mowing may influence *L. maculicollis* establishment in putting greens. Mowing has been shown to negatively impact other turfgrass insects that lay eggs within putting surfaces. Eggs of black cutworm (*Agrotis ipsilon* Hufnagel), a major pest of bentgrass greens in the transition and cool-season regions of the United States, are removed with regular mowing, and even larvae may be killed when mowing is performed early in the morning (Williamson and Potter 1997a). However, unlike *A. ipsilon*, *L. maculicollis* eggs and early-instar larvae develop within the stem of the turfgrass plant and therefore may not be as affected.

Much of our knowledge of *L. maculicollis* behavior, growth and development, and population dynamics has come from research over the past decade. However, all previous studies have been conducted in turfgrasses grown at 1.25 cm (0.500 in) or greater, which hinders our ability to predict damage or to make recommendations for putting green management. We examined the influence that mowing has on *L. maculicollis* adult and larval survival to determine the potential for culturally controlling *L. maculicollis* in putting greens. Specifically, we sought to 1) determine the probability of *L. maculicollis* adults surviving mowing, 2) determine the ability of adults to oviposit in plants maintained at heights-of-cut found on putting greens, and 3) to determine if larvae can develop to damaging stages (late instars) in short-mown turfgrasses that are routinely mowed. It is our hope that the findings of this research will aid in determining likelihood of *L. maculicollis* establishing within putting greens, as well as the usefulness of insecticide treatments to these areas. A better understanding of *L. maculicollis* behavior and population development in putting greens may allow turfgrass managers to reduce the frequency of chemical applications and develop novel, nonchemical controls for managing both susceptible and pyrethroid-resistant populations.

Materials and Methods

Insect Collection and Preparation

Adult *L. maculicollis* used in laboratory and field experiments were collected using a modified leaf blower-vacuum (Echo ES 255, Lake Zurich, IL; McGraw and Koppenhöfer 2009) from insecticide-free golf course fairways located in central Pennsylvania (Lancaster Country Club, Lancaster, PA; Sinking Valley Golf Club, Altoona, PA, Bucknell University Golf Course, Lewisburg, PA) and New York (Sleepy Hollow Country Club, Briarcliff Manor, NY). Insects used in Experiment 1 (below) were collected from golf courses between 25 June and 1 July, 2015 and on 27 June, 2016. Insects used in Experiments 2 and 3 were collected during the initial overwintering–adult migration on to the short turf in spring in 2015 (10 April–14 April) and 2016 (18 April–22 April). Vacuum-collected adults were placed in groups of 50–100 in plastic containers fit with mesh lids. The containers were placed into a cooler and transported to the Turfgrass Entomology Laboratory at Pennsylvania State University (University Park, PA). Adult viability was assessed upon arrival before the insects were transferred to a new container with a moistened paper towel. The containers were held in an incubator at 23 °C (2015) or 10°C (2016), with a photoperiod of 12:12 (L:D) h until use in experiments (<2 d).

Experiment 1: Effects of Mowing Height on Adult *L. maculicollis* Removal

The effect of mowing height on adult *L. maculicollis* removal and survival was assessed in controlled greenhouse studies. Turf used in this experiment was removed from a *P. annua* research putting green (Land Management Resource Center, University Park, PA) immediately following mowing. The area was enclosed on all sides by linear pitfall traps to limit the movement of endemic *L maculicollis* onto the turfgrass. Treatments consisted of one of the three putting green mowing heights (2.54, 3.18, and 3.81 mm or 0.100, 0.125, and 0.150 in) representing a range putting green height-of-cut found across the region (McGraw and Koppenhöfer 2017). We refer to these treatments as low-, medium-, and high-putting green treatments from this point forward. In 2016, collar- (6.35 mm; 0.250 in) and fairway-height (12.7 mm; 0.500 in) treatments were included. Cores (7.62 cm in diameter by 4.8 cm deep) were removed using a turf plugger (Turf Tec International, Tallahassee, FL), placed into plastic bags for transport to the laboratory, and transferred into plastic containers of the same dimension. The soil surface of the turf core was made level with the upper rim of the container so that the height-of-cut could be accurately measured in the greenhouse from the soil surface to top of the mower bed knife.

Adults were marked with ultraviolet (UV) ink (Dykem, Olathe, KS) to allow for easier tracking during mowing experiments. Adults were placed in the incubator for 1 h after marking to allow the UV ink to dry and to assess the effect of the mark on insect behavior. After the holding period, viability was assessed and weevils were placed in groups of five on a turf core. The cores were held at 23°C for 24 h to allow the weevils to acclimate to their environment and settle into the turf canopy. The period also served as a realistic representation of the time between mowing events on a putting green. After 24 h, the turf samples containing *L. maculicollis* adults were taken to a greenhouse where mowing treatments were applied.

Mowing treatments were applied using a battery-powered reel mower suspended on a track over a greenhouse bench. Prior to each experimental run, the mower height was calibrated using a dial micrometer, measuring from the rim of the container (or soil surface) to the top of the mower's bed knife. Adjustments to the height-of-cut were made by adding or removing sheets of computer paper placed under the container holding the turf sample. Turfgrass cores were mowed in the greenhouse at the same height-of-cut from which they were mowed 24 h previously in the field. Each experimental run began by moving the reel mower over a turfgrass core without weevils to ensure that the machine was properly functioning. The second pass was performed with turfgrass cores containing weevils. The order in which mowing treatments were applied was randomized after each treatment. The mower was fit with a basket in front of the reel to capture clippings and any weevils that were ejected by the blades. Adult mortality was based on the number of weevils collected through a combination of manual examination of the turf core and clippings, followed by the use of a UV light to detect the marked weevils, and, where necessary, saline solution extraction. The combination of methods allowed us to account for each individual tested. Adults that were collected alive, but were injured by the mower (damaged or cracked elytra), were recorded as dead. All experiments were conducted between 1100 and 1430 hours. Each mowing treatment was replicated 10 times per experiment, using a new core and weevils for each experimental run. Three experiments were conducted in both 2015 and 2016, for a total of 60 replicates per treatment.

Experiment 2: Effects of Mowing Height on *L. maculicollis* Oviposition in No-Choice Assays

A no-choice field experiment was conducted to determine if mowing height affected *L. maculicollis* oviposition (total eggs and placement) in three greens-height treatments in 2015. In 2016, a fourth treatment (7.62 mm; 0.300 in) was included to represent the mowing height found on putting green collars. *Poa annua* cores (2.8 cm in diameter by 9 cm in deep) were removed using an Oakfield soil core sampler from the same research putting greens used in Experiment 1. The turfgrass area from which plugs were removed was enclosed on all sides with a linear pitfall trap to ensure that *L. maculicollis* populations did not move into the plots and to prevent adult movement between treatments.

Turf plugs were removed immediately following mowing and placed into 50-ml conical tubes (Corning, Corning, NY) of the same diameter (2.8 cm) as the cores. Sand was placed under the plug to ensure that the surface of the turf was even with the 40-ml mark on the tubes and to ensure uniformity between samples before mating pairs (1 male and 1 female) were added. A hole was drilled in the cap of the conical tube and fit with a fine mesh (324-mesh, 7.2 by 7.2 openings per cm^2) to provide ventilation but prevent adults from escaping. Tubes were manually inserted into the soil within the research putting green so that the top of the turfgrass inside the conical tube was flush with the surface of the existing turf. After 48 h, cores in tubes were brought to the laboratory and examined with a dissection microscope (40× magnification). Adults recovered from each tube were transferred to a new conical tube containing a fresh-mown sample to ensure that females were provided with hosts of a uniform height-of-cut throughout the experiment. At this time, the tillers of the old plug were inspected for eggs by peeling back each leaf sheath from the stem. The number and the location of eggs (e.g., loose or on the outside of the plant, within the stem, or between the leaf and the stem) were recorded. In total, 20 mating pairs were observed for each mowing treatment in both years. The same mating pair was observed for 18 d (nine egg inspections), or the length of time that the majority of eggs are oviposited when confined (B.A.M., unpublished data).

Experiment 3: Effects of Mowing Height on *L. maculicollis* Larval Growth and Development

The ability of larvae to develop to damaging stages (i.e., fourth and fifth instars) in golf course putting green-height turf was assessed in controlled field studies. Mowing height treatments consisted of the same three greens height-of-cut and a single collar height-of-cut as described in the previous experiments. Field-collected adults (1 male + 1 female) were placed into PVC arenas (12 cm in height by 10 cm in diameter) within a plot (60 by 180 cm) maintained at one of the four mowing heights. The enclosures were driven 2 cm into the ground with a soil tamper and the edges of the containers painted with Insect-Slip (Fluon, BioQuip Inc., Rancho Dominguez, CA) to prevent weevils from escaping. All treatments were separated from one another by linear pitfall traps.

Adults were allowed to oviposit in the arenas for ∼30 growing degree days (simplified sine method with a base of 10°C), as calculated by an onsite weather station (WatchDog 2400, Spectrum Technologies, Aurora, IL). A holding period based on growing degree days was selected to allow for consistency between experiments and as a compromise between the potential number of eggs laid and turfgrass growth. After this period (5–7 d), the containers and adult weevils were removed, and mowing treatments resumed. Two arenas from each replicate were removed each week for 7 wk. Each treatment was replicated nine times, with each replicate containing 14 PVC enclosures. This allowed for 18 larval stage assessments per treatment per week from first instar through pupal eclosion.

Weevil stages in cores were estimated in the laboratory by employing either a high heat extraction (early-instar larvae) or manual examination followed by soaking in a saturated saline–water solution (older larvae). The effect of mowing height on larval fitness was measured as the average weight of fifth-instar larvae, as this stage was the most effectively extracted.

Statistical Analyses

Statistical analyses were conducted using Statistix 9.0 (2003) software package (Tallahassee, FL). One-way analysis of variance (ANOVA) was used to determine the effects of mowing height on *L. maculicollis* adult removal and survival, total number of eggs laid in no-choice assays, and differences in larval development by mowing height treatment. The proportion of eggs placed within the stem of the plant was arcsine-transformed, and larval counts and weights (fitness) in no-choice assays were square-root transformed (+0.5) to normalize the variance of the data. Shapiro–Wilk tests of normality were performed to ensure that the data conformed to a normal distribution prior to means separation through ANOVA. Where significant differences were detected ($\alpha = 0.05$ level), single degree of freedom polynomial contrasts were constructed to assess linear, quadratic, and cubic relationships between insect stages (adults and eggs) and mowing treatments. Additionally, contrasts were performed to determine differences between the means of individual mowing treatments and combined group means (e.g., low- vs. medium- + high-putting green-height treatments).

Results

Experiment 1: Effects of Mowing Height on Adult *L. maculicollis* Removal

An inverse relationship between mowing height and adult removal was observed in both years of the study (Fig. 1). Strong statistical differences were detected between the total number of weevils removed from the low greens-height treatment compared with that of the medium and high-putting green treatments in 2015 ($F = 31.4$; df $= 2, 57$; $P < 0.0001$) and 2016 ($F = 40.0$; df $= 4, 145$; $P < 0.0001$). The total number of adults removed by mowing displayed strongly significant ($P \leq 0.0001$) linear and quadratic trends

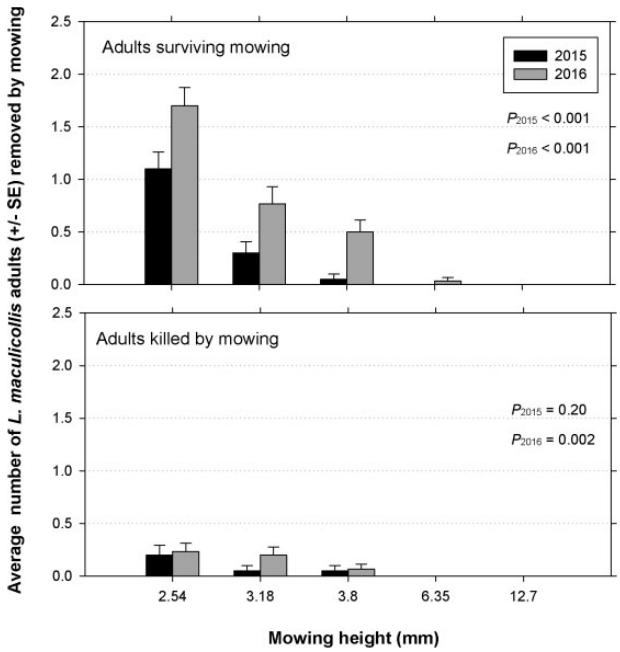

Fig. 1. Average number of *L. maculicollis* adults of five infested that survived or were killed by putting green- (2.54 to 3.81 mm; 0.100 to 0.150 in), collar- (6.35 mm; 0.250 in), and fairway-height mowing treatments (12.7 mm; 0.500 in) in greenhouse studies (2015–2016). The number of adults surviving mowing and those killed by the mower were analyzed separately by year. Polynomial contrasts were performed where significant effects were detected by ANOVA at $\alpha = 0.05$ level.

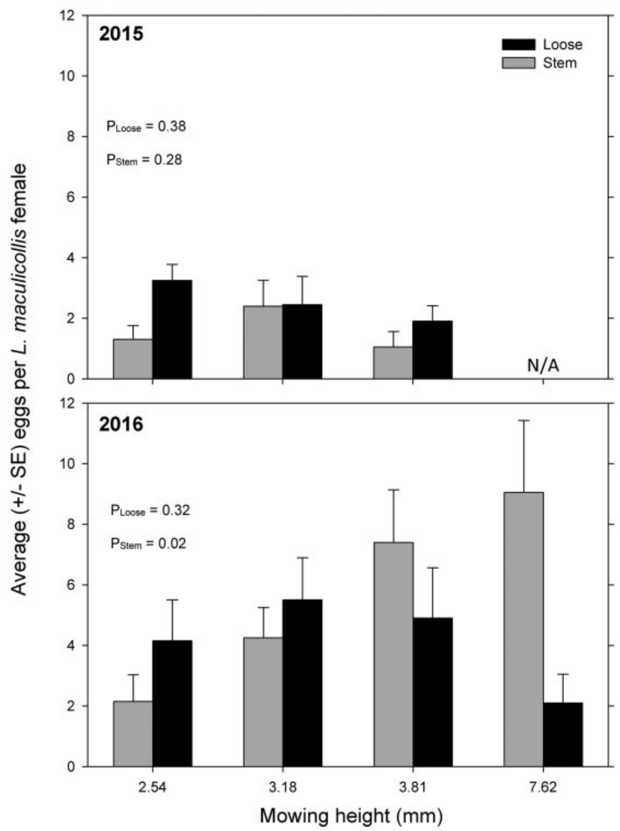

Fig. 2. Average number of *L. maculicollis* eggs laid loosely or outside the plant versus inside the stem at putting green- (2.54 to 3.81 mm; 0.100 to 0.150 in) or collar-height (7.62 mm; 0.300 in) turf in no-choice oviposition studies (2015, 2016). Polynomial contrasts were performed where significant effects were detected by ANOVA at $\alpha = 0.05$ level.

with mowing heights in 2015 and 2016, as well as strongly significant cubic trends in 2016 trials. The lowest mowing height was capable of removing an average of 26% (±5 SE) and 38% (±4.8)of adults in 2015 and 2016, respectively. This treatment was significantly different from medium- (7 ± 3.2% and 19.4 ± 4.6%) + high-putting green treatments (2 ± 2% and 11.4 ± 3.4%) in 2015 (F = 30.2; df = 1, 57; $P < 0.0001$) and 2016 (F=14.3; df = 1, 145; $P < 0.0001$). Additionally, the combined putting green treatments were significantly different from the collar- (0.6%) and fairway-height treatments in the 2016 study (F = 24.5; df = 2, 145; $P < 0.0001$).

Mowing did not have a significant effect on adult survival, as most adults collected from each treatment were alive (79% of the total removed insects in six of the seven treatments). In 2015, no significant differences were detected between the number of adults that were killed by the mower for low- (4 ± 1.8%), medium- (1 ± 1%), or high- (1 ± 1%) putting green treatments (F = 1.68; df = 2, 57; P = 0.20). Significant differences were detected between mowing treatments in 2016 (F = 4.42; df = 4, 145; P = 0.02) when fairway- and collar-height turf was included in the experiment. The ANOVA contained significant linear (P = 0.002) and quadratic (P = 0.01) relationships between adult mortality and mowing heights. Additionally, significantly more adults were killed in greens-height treatments than in collar- + fairway-height turf (F = 3.01; df = 2, 145; $P < 0.001$).

Experiment 2: Effects of Mowing Height on *L. maculicollis* Oviposition in No-Choice Assays

Adult *L. maculicollis* were capable of ovipositing in all three greens-height mowing treatments in no-choice studies (Fig. 2). No significant differences were detected in the total number of eggs laid per female by mowing treatment in either 2015 (F = 0.83; df = 2, 57; P = 0.44) or 2016 trials (F = 0.96; df = 3, 76; P = 0.42). Mowing height had an effect on oviposition behavior, as eggs were not only found inside stem as previously reported, but also on the exterior of the plant ("loosely"). In 2015, more than twice as many eggs per female were deposited loosely (3.25 ± 0.53) compared with within the stem (1.03 ± 0.45) in the low greens-height mowing treatment, and fewer loose eggs were detected as mowing heights increased. However, no significant differences between treatments or significant trends in egg placement were detected. Analyzing the proportion of loose eggs of the total oviposited by treatment uncovered significant differences between treatments (F = 3.15; df = 2, 57; P = 0.05), which could be explained by linear trend (F=2.03; df = 2, 57; P = 0.04) or a decline in loose eggs with increased mowing height.

The number of eggs laid per female was greater in 2016 experiments, and significant relationships between egg placement and mowing height were detected. A significant linear relationship was observed between eggs placed in the stem and increased mowing height (F = 0.02; df = 3, 76; P = 0.02), but not between loose eggs and mowing height (F = 1.18; df = 3, 76; P = 0.32). Significantly fewer eggs were oviposited in the low-putting green-height treatment compared with other treatments (F = 2.11; df = 1, 76; P = 0.01), which may have affected the ability to detect a significant polynomial trend for egg placement by mowing height. Significant differences were detected in the proportion of eggs laid loosely (F = 4.76; df = 3, 76; P = 0.004) and in-stem (F = 4.20; df = 3, 76;

$P = 0.008$), with each polynomial contrast demonstrating strongly significant linear response for loose eggs ($F = 3.62$; df = 3, 76; $P = 0.002$) and linear ($F = 2.42$; df = 3, 76; $P = 0.009$) and cubic ($F = 1.89$; df = 3, 76; $P = 0.02$) responses between in-stem eggs and mowing height.

Experiment 3: Effects of Mowing Height on *L. maculicollis* Larval Growth and Development

Putting green mowing height did not affect *L. maculicollis* larval abundance or the ability for larvae to develop to damaging stages (Fig. 3). Early-instar larvae were too scarce to perform statistical analyses or obtain accurate assessment of weight and therefore were omitted from the results. There were no statistical differences in the average number of fourth and fifth instars, pupae, or total stages recovered by mowing treatment ($F \geq 0.08$, df = 3, 104; $P \geq 0.61$). Additionally, no significant effects of mowing height on larval fitness were detected as measured by weight gain for fifth-instar larvae ($F = 0.14$; df = 3, 8; $P = 0.94$). On an average, fifth instars weighed 6.4 (± 0.45 SE), 6.9 (± 0.39), 6.6 (± 0.52), and 6.6 (± 0.62) mg for low-, medium-, and high-putting green, and collar treatments, respectively.

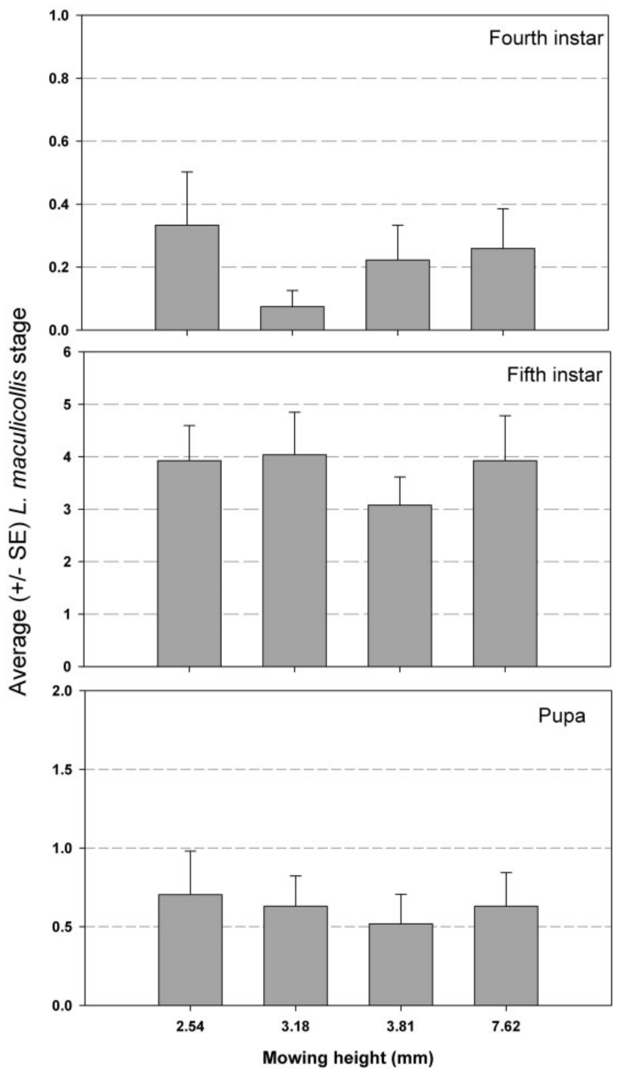

Fig. 3. Mean number of *L. maculicollis* fourth- and fifth-instar larvae, and pupae recovered from putting green- (2.54 to 3.81 mm; 0.100 to 0.150 in) or collar-height (7.62 mm; 0.250 in) height-of-cut in no choice field studies. No significant differences between mowing treatments were detected for any life stage.

Discussion

This study is the first to characterize *L. maculicollis* oviposition behavior and larval development in putting green-height turf. Prior to this study, it was not known whether *L. maculicollis* adults were capable of surviving on and ovipositing within short-mown putting surfaces, and whether larvae were able to develop to damaging stages in plants maintained at the lower end of putting green mowing heights. Our results demonstrate that *L. maculicollis* adults are capable of surviving mowing at putting green-height turf, readily accept the short-mown host plants as oviposition substrates, and larval development is unaffected by mowing height. This suggests that *L. maculicollis* pose a threat to golf course putting greens, despite damage being rarely observed in these areas. However, the probability of adults establishing in these areas (and possibly the need for frequent insecticide applications) may be reduced on the estimated 35% of golf courses in the region that are maintaining putting surfaces at or near 2.5 mm (McGraw and Koppenhöfer 2017).

Greenhouse studies demonstrated that mowing height has a significant effect on adult removal, as between 26% and 38% of adults were removed with a single low mowing treatment (2.54 mm; 0.100 in). Given that putting surfaces are mowed almost daily throughout the growing season, and sometimes twice in one day (i.e., "double cutting"), the additive effect of mowing on adult abundance on putting surfaces is likely to lead to very low population densities. Conversely, at higher heights-of-cut, such as those found on collars and fairways, very few adults can be expected to be removed, as <1% of the total adults infested in greenhouse studies were removed. This may explain why damage is rarely observed on short-mown putting greens, yet is common on adjacent collars and fairways receiving the same chemical, and similar cultural inputs. In a recent survey of golf course superintendents in the region, 26% reported experiencing damage to putting surfaces (McGraw and Koppenhöfer 2017). However, of those reporting damage, two-thirds maintained putting surfaces at heights greater than the regional average (3 mm; 0.150 in). It is important to note that the benefits gained in *L. maculicollis* removal with decreasing mowing heights on putting surfaces are likely to be lost in the biological and economic costs gained. Lower mowing heights create increased stress on the turf, decrease root length, and require greater inputs (e.g., fertilizer, water) and labor costs to maintain its survival (Vargas and Turgeon 2004). Therefore, we do not propose further reducing mowing heights solely as a means of control, but rather suggest that golf courses that are currently managing surfaces near 2.5 mm or below may reduce the intensity or frequency of insecticide applications targeting *L. maculicollis*. Increasing the frequency of mowing in spring (e.g., double cutting) when overwintering adult abundance is greatest may lead to even greater reductions in adult density, as plant material that is not removed in the first pass is removed when mowed perpendicular to the first pass. The practice of double cutting serves to increase the smoothness and speed of the putting surface (Karcher et al. 2001), but requires increased labor and may be stressful to the turf. Therefore, it cannot be practiced constantly throughout the year. However, future studies may investigate the impact that double cutting has on adult *L. maculicollis* abundance in golf course greens in the spring when cool-season turfgrasses are growing vigorously and under less stress than in summer.

Our studies demonstrated that the majority of adult *L. maculicollis* survive mowing, and therefore may reinvade turfgrass stands adjacent to areas where grass clippings are discarded. Generally, clippings are spread in the higher-mown turf ("rough") surrounding the putting green, or combined with all turfgrass clippings in a central location. The adult survival within and the daily accumulation of clippings suggests that disposal sites may harbor significant numbers of adults over time. The eggs of black cutworm (*A. ipsilon*), a severe pest of creeping bentgrass putting greens and tee boxes throughout much of the United States, are also capable of passing through the mower's reel unscathed (Williamson and Potter 1997a). The female oviposits on the distal end of the turfgrass blade (Williamson and Shetlar 1995, Williamson and Potter 1997b), thus their removal from putting surfaces as well as higher heights-of-cut are possible. Williamson and Potter (1997a) demonstrated that mowing putting surfaces (<4.8 mm) may remove as much as 91% of eggs. However, egg survival on grass clippings was shown to be high (>90% in the laboratory), and surviving larvae were observed migrating back toward putting surfaces. Thus, collecting and disposing clippings away from putting greens have become common practices for managing black cutworm. Similarly, turfgrass managers must be aware that clippings containing live *L. maculicollis* need to be discarded far from short-mown turfgrass areas, as *L. maculicollis* are capable of traveling hundreds of meters to find suitable host plants (Diaz and Peck 2007). Future studies are needed to determine what effect, if any, the management of clipping piles (e.g., composting, burying) has on *L. maculicollis* survival.

Listronotus maculicollis oviposition behavior on putting surfaces deviated from what has been observed in studies conducted on higher-mown turf. Previous studies conducted with caged field-collected insects suggest that females lay eggs into an oviposition hole, with the majority of eggs placed near the base of the stem (Cameron and Johnson 1971). The mowing heights in these studies was not noted, though we can be assured that these treatments were higher than modern putting green-heights, given the inability of that era's mowers to achieve heights-of-cut <4.7 mm (0.187 in; Nikolai 2005). In our studies, females were capable of laying eggs in all mowing height treatments, yet a significantly higher proportion of eggs were laid outside the turfgrass stem as putting green-heights decreased. We cannot determine from these no-choice assays whether females preferentially or equally oviposit within putting green- or collar-height turf. However, eggs laid outside of the plant on putting greens are likely to be much more vulnerable to predation and environmental extremes (e.g., heat, desiccation) than eggs that have been oviposited inside of the turfgrass stem. Numerous predators inhabit putting greens, including ground and rove beetles, and ants (López and Potter 2000). *Lasius neoniger* Emery is a major predator of golf course insect pests, including *A. ipsilon* and *Popillia japonica* (Newman) eggs. López and Potter (2000) found that *L. neoniger* was responsible for removing ~30% of *A. ipsilon* and 40% of *P. japonica* eggs from golf course fairways. The impact that *L. neoniger* had on *A. ipsilon* egg removal was even greater on putting surfaces as ~65% reductions were observed in a 22-h period. The impact that predators have on *L. maculicollis* eggs in golf course putting greens is unknown. However, predation may contribute to further reducing populations on putting surfaces, particularly on courses mowing putting greens at the lower end of the spectrum. Golf course superintendents often consider *L. neoniger* to be a nuisance pest, as ant mounds can dull mower blades, smother turf, and compromise the smoothness of the playing surface. Thus, turf managers typically make broad-spectrum insecticide applications to control mounding in early spring (Potter 1998, Maier and Potter 2005). However, these early-season insecticide applications targeting *L. neoniger* on putting surfaces, as well as those targeting *L. maculicollis* adults, may diminish the impact that these and other beneficial insect communities have on egg predation.

Traditionally turfgrass managers have sought to preventively control larval feeding damage by targeting adults with broad-spectrum insecticides (Vittum et al. 1999). Putting greens often receive multiple adulticide applications in spring to maintain the functional qualities of the surface while compensating for the short-residual activity of the products. Only two insecticide classes (pyrethroids and organophosphates) provide acceptable adult control (~40–90% reductions) in most populations (Koppenhöfer et al. 2012). This has created challenges in slowing the development of insecticide resistance, and highlights the need to develop nonchemical means for controlling adults. Our findings suggest that mowing has potential to replace adulticides on putting surfaces maintained at or <2.5 mm. However, the low (to no) tolerance for larval damage in putting surfaces combined with the expected 26–38% adult removal in one mowing may necessitate combining cultural and chemical controls (e.g., larvicide). Several insecticide classes work effectively when applied against larvae (Koppenhöfer et al. 2012), and in general, have improved residual activity and greater selectivity. A recent survey estimates that most superintendents are already using larvicides (94%), and therefore eliminating adulticides from short-mown putting surfaces would not require great changes to current management practices. However, more research is needed to determine the cumulative effect of daily mowing on natural adult population establishment on putting greens and possibly methods to improve removal before we can conclusively determine the probability of damage occurring when eliminating adulticides, if not all insecticides, on putting greens.

Our studies provide greater insight into understanding *L. maculicollis* ovipositional behavior and the potential for damaging short-mown putting surfaces. Because *L. maculicollis* readily oviposits and has the ability to develop to damaging stages (i.e., fourth- and fifth-instar larvae) within the lowest putting green-heights in the region, turfgrass managers assume some degree of risk to turf loss by withholding insecticide applications from these areas. However, the impact that single mowing events have on adult removal is encouraging for developing cultural control programs, or at the very least, developing strategies to integrate cultural and chemical controls to lessen the need for chemical insecticides on putting surfaces. More research is needed to determine important factors that influence *L. maculicollis* surface activity to improve mechanical removal from surfaces. Until that time, mowing alone cannot be viewed as a viable replacement for synthetic insecticides. Future research will examine the individual and combined effects that other putting green management practices (e.g., topdressing, irrigation, fungicide applications, and plant growth regulation) have on *L. maculicollis* population development to develop best management practices for putting greens.

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