ABSTRACT. Two species of crane flies (Diptera: Tipuloidea) introduced from Europe, *Tipula oleracea* L. and *T. paludosa* Meigen, have become established across portions of northeastern United States and present an economic concern to the production sod industry. The presence of both species in northeastern U.S. sod production fields was confirmed in 2009, and on two separate occasions *T. paludosa* larvae were detected after delivery of sod from producer to consumer. Infestation of production fields poses a threat to the quality of the developing sod product as well as a conduit for human-mediated range expansion of an invasive species. As the unintentional transport of larvae in shipments of sod is a major repercussion, much of the burden from invasive crane fly establishments may fall on the consumer. We propose and explain a core set of best management practices for consideration and adoption by sod producers in northeastern U.S. Crane fly life history and ecology is first discussed as a key element to recognizing and locating infestations in production fields. The scientific rationale behind our recommendations for interventions is then discussed with respect to basic Integrated Pest Management (IPM) elements (monitoring populations, damage thresholds, cultural management, chemical and biological control). The recommendations are further summarized in a checklist with respect to sod production cycle (preharvest, harvest, postharvest). The goal of these practices is the prevention of in-field infestations, the protection of developing sod, the assurance of crane fly-free shipments, and the safeguarding of commercial customers.

Key Words: invasion biology; turfgrass pests; soil insects; *Tipula oleracea*; *Tipula paludosa*
species, detecting and understanding the causes of crane fly larval feeding damage, and understanding the crane fly developmental cycle in relation to the sod cropping cycle. Intervening in cases of crane fly detection means managing invasive crane flies through the monitoring of adult and larval populations, understanding damage thresholds, enacting cultural management, using chemical and biological controls, and carefully monitoring during harvest. The IPM recommendations provided here are aimed at informing producers in an effort to prevent in-field infestation and safeguarding consumers who receive commercially produced sod products.

**Crane Fly Life History and Ecology.** **Crane Fly Diagnosis.** Accurate species diagnosis is an important primary step in any IPM program (Radcliffe and Hutchinson 2009) (Table 1). The two species of interest, *T. oleracea* and *palludosa*, are part of a larger group of flies commonly called crane flies, of which there are nearly 15,000 species worldwide and over 1,500 species in North America (Oosterbroek 2010). Therefore, making accurate species identifications, and linking this to an understanding of natural history, behavior, and damage expression, are vital first steps in the BMPs presented here (Table 1). Like most crane flies, *T. palludosa* and *T. oleracea* are most visible as adults when they resemble oversized mosquitoes (Fig. 1). Adults average 2.5–3.0 cm in length, are tan in overall coloration, and have wings with a dark band of coloration along the leading edge. Adults are nondamaging to turfgrass or sod and should never be targeted with control measures, as reducing adult fly numbers will not significantly impact larval abundance. Distinguishing the two invasive species from other native species in any of the insect life stages can be difficult, as there are hundreds of crane flies native to the region and many can easily be confused for the invasive species. No native crane fly species is currently known to occur in, or be damaging to, NE sod. Several online resources are available for aid in identifying adult specimens (Table 2), and although many native species can easily be distinguished from invasive crane flies, a definitive identification may require a diagnosis from a trained specialist. Most of the crane fly’s life cycle is actually spent underground as a larva (Fig. 2). Larvae are 3–4 cm long when mature and drab gray or brown in color. Identification of larvae to species generally is difficult and usually requires the guidance of an expert trained in insect diagnostics. Crane fly larvae, however, are easily differentiated from other turf pests such as white grubs (Vittum et al. 1999).

**Geographic Distribution.** Both the large scale (county and state distribution maps) and fine scale (individual fields) distribution patterns for both invasive crane fly species must be understood to direct scouting and monitoring programs that later direct intervention efforts (Table 1). Through 2010, five states in the NE have confirmed populations of invasive crane flies: Ohio (*T. oleracea*), Massachusetts (*T. oleracea*), Michigan (both species), New Jersey (*T. oleracea*), and New York (both species). The current distributions of both species are available through the National Agricultural Pest Information System (http://pest.ceris.purdue.edu/index.php).

**Damage Recognition.** It is expected that all grass species grown commercially for sod in NE United States would adequately serve as suitable host plants for larval development (Pesho et al. 1981, Stahnke et al. 1993, unpublished data). Turf damage is attributed to both above and below ground feeding activities by the larvae. Larvae cause damage akin to black cutworm (*Agrotis ipsilon* Hufnagel) larvae, grazing above ground portions of the stem and foliage. By feeding on and disrupting below ground portions of the plant, crane flies can cause other damage similar to white grubs (Coleoptera: Scarabaeidae). Such feeding activities in production sod could lead to a less marketable product through loss of tensile strength, thinning, and dieback. Visual damage attributed to crane fly larval feeding has been detected in sod production fields in the NE and PNW United States (G. Stahnke, personal communication). Direct damage to sod in the NE caused by larval crane fly feeding should be low if harvested within 2 yr, similar to damage caused by other insect pests of sod (Siligato 1999, CIPT 2010). Damage will be higher in areas with water-saturated soils where feeding damage is compounded with turf stress. Indirect damage may also occur because of predators (e.g., birds, raccoons, skunks) that disrupt turf when foraging for crane fly larvae (Peck et al. 2010).

**Insect Development and Cropping Cycle.** NE sod production typically occurs on a 14–18 mo cycle but may be up to 24 mo in some colder climates. Harvest occurs all at once or as the market demands (Siligato 1999, Charbonneau 2003). To illustrate the relationship between NE sod production cycles and crane fly life cycles, Fig. 3 depicts a typical production timeline for an autumn-seeded Kentucky bluegrass or Kentucky bluegrass mix sod field with a production cycle of ∼14 mo. Invasive crane flies complete one (*T. palludosa*) or two (*T. oleracea*) generations per year, passing through the egg, larva, pupa, adult, and the life cycle repeats.

**Table 1. Best management practices checklist for reducing invasive crane flies in sod production**

| Pre-harvest | Harvest | Post-harvest |
|-------------|---------|--------------|
| Life history and ecology | Life history and ecology | Life history and ecology |
| ✔ Become familiar with species identification and insect life cycles. | ✔ At the time of harvest, determine the life stage of each species to better direct monitoring during harvest | ✔ At the time of harvest, determine the life stage of each species to better direct monitoring during harvest |
| ✔ Look for signs of crane fly feeding damage in production fields and surrounding turf. | ✔ | ✔ Sod with a threat of infestation should not be shipped beyond the current distribution of either species. |
| Intervention | Intervention | Intervention |
| ✔ Utilize mowing and field maintenance as times to scout for adult flies during times of adult emergence. Follow-up with scouting of all field margins twice during the times of adult emergence. | ✔ Look for the presence of larvae, whole or cut, at the soil level during sod harvest. | ✔ Monitor harvested sod, in roles or pallets, for the presence of larvae. |
| ✔ Scout for adult flies in areas of permanent turf surrounding production fields. | ✔ if larvae are detected, send specimens for identification | ✔ If infested sod is sold to consumers before intervention, offer on-site rescue treatments. |
| ✔ If adults are detected, follow-up with directed larval scouting in areas of adult activity. | ✔ To certify a crane fly free product, apply curative insecticidal treatments to the remaining field. | ✔ Enact regular monitoring of fields with previous larval infestation during future plantings. |
| ✔ If larvae are detected, monitor pop levels and/or apply curative treatments. | ✔ Allow for complete larval mortality after curative treatments before cutting and shipping sod. | ✔ Enact cultural management to reduce the likelihood of larvae within sod fields. |
| ✔ Consider enacting cultural management to reduce the likelihood of larvae within sod fields if adults or larvae are detected. | | |
and adult life stages. More information on crane fly life cycles may be found in Laughlin (1960, 1967); Wilkinson and MacCarthy (1967); Jackson and Campbell (1975); Meats (1975); Blackshaw and Coll (1999); and Peck et al. (2010).

Seeding in NE sod production occurs in the late summer or early autumn (occasionally in the spring). If fields were left fallow over summer before autumn planting, invasive crane fly larvae should not be present in fields at the time of planting. Fields seeded in August and September may have adult emergence of both species. Adult flies (both *Tipula oleracea* and *T. paludosa*) are present over a period of 3–4 wk during emergence. Adult flies will mate and lay most eggs all within one (*T. paludosa*) or 3–4 (*T. oleracea*) days. Females of each species lay up to 200–300 small black eggs (Fig. 2) at or near the soil surface. Eggs hatch in one (*T. oleracea*) or 1.5–2 (*T. paludosa*) weeks into active larvae. Eggs are sensitive to drought and require moisture to survive; thus, areas that maintain high soil moisture are at higher risk for egg deposition and larval survival. Feeding damage to early developing sod has been observed during the first autumn after planting in the PNW (G. Stahnke, personal communication), but has not been observed in NE sod fields.

Usually, by the next spring the sod will have developed to a stand that will readily support crane fly populations. If larval populations are at or above action threshold levels, in-field damage could be detectable. Feeding damage to turf in the NE generally occurs during April and May when invasive crane fly larvae feed voraciously on turfgrasses and grow rapidly. If fields were left bare over the winter and spring seeded it is unlikely that larvae would be present in fields. In late April and early May, *T. oleracea* larvae finalize their larval growth before pupation and adult fly emergence. The factors influencing *T. oleracea* oviposition are not well studied, however, the occurrence of larvae in soils with greater moisture would indicate that these areas are at higher risk for egg deposition. *Tipula paludosa* larvae will grow through the spring to active fourth instars. The larvae then enter an inactive state and may be found deeper (3–5 cm) in the soil profile over the summer and pupate in September to October.

In September and October when the sod nears 14 mo of development, sufficient rhizome and root development will allow for a harvestable sod product. Autumn harvested fields are unlikely to show visible signs of sod damage from crane fly feeding. As adult emergence of both *Tipula* species occurs in late August through early October, fields are particularly susceptible to infestation during the autumn harvest period. If harvest happens during autumn, larvae will be small first instars (Fig. 2) and difficult to detect. If harvest occurs the next spring, larvae will again be either fourth (*T. oleracea*) or third-fourth (*T. paludosa*) instars. Regardless of season, the short shelf life and quick delivery of harvested sod helps to facilitate survival of invasive crane flies in sod transported from producer to consumer.

**Intervention.** Reducing the impact of invasive crane flies in sod is a function of monitoring insect population levels, minimizing the favorability of the sod environment through cultural management methods, responding to high crane fly densities with chemical or biological controls, and carefully monitoring harvest. Managing invasive crane fly populations will decrease the occurrence of preharvest in-field damage and lessen the probability of transporting crane fly larvae in sod after harvest (Table 1).

**Monitoring.** Scouting for adult flies should be emphasized initially to assess whether invasive crane flies are present in and around production fields (Table 1). The presence of adults will help indicate areas where eggs are likely to be deposited in fields; these fields...
should be sampled further for larvae and feeding damage. Adult flies are easily captured with an insect or butterfly net. When collecting specimens for identification, it is important to get several individuals. Specimens may be placed in small vials containing 70% ethanol. Before shipping for identification, the ethanol should be decanted (drained off) and the specimens sealed in a leak-proof container. Scouting should coincide with the two periods of adult emergence (Fig. 3). The period of emergence may differ between years or geographic regions. Therefore, scouting should occur over several weeks. Adults are most active between 8:00 and 11:00 a.m. and between 5:30 p.m. and dusk. During the day, adults are less visible when they rest in turf, tall brush, undergrowth, and other vegetation in field borders. Scouting for adults easily may be accomplished during mowing and other field maintenance activities to determine if further scouting for larvae is warranted. In addition to checking for adult crane flies in production fields, scout for them in permanent grassy field borders. Scouting for adults easily may be accomplished during mowing and other field maintenance activities to determine if further scouting for larvae is warranted. In addition to checking for adult crane flies in production fields, scout for them in permanent grassy habitats around fields (i.e., office and building grounds, field margins, ditches, stream or pond margins). When scouting areas surrounding fields, shake the limbs of shrubs and low lying tree branches, as flies will often be found there.

Larval scouting within production fields should be guided by detection of adult flies and by visual observations of sod damage caused by crane fly larvae or by predators searching for larvae (e.g., starlings, crows, and skunks) (Table 1). Larvae are likely to be found in production fields with high soil moisture (Milne et al. 1965, French 1969). Larvae typically are found in the thatch or within the top 3 cm of soil, but may be 5 cm deep during the summer months or dry periods. As the early developmental stages (first and early second instar) are difficult to detect, scouting may not prove fruitful until larvae are at least third or fourth instar (Fig. 2).

Scouting for larvae may be used to estimate population densities to determine the need for intervention. This is accomplished either by removing test strips using a sod cutter or removing soil cores using a golf course cup-cutter. When using a sod cutter, remove a 0.5–1.0 m (2–3 foot) long strip of turf. The soil surface from where the sod was removed first should be scouted for full or dissected larvae. Next, manually search for larvae within the soil and in the thatch of the sod itself by breaking the turf apart. This method will give the most accurate estimate of larval density. Removing soil cores with a golf course cup-cutter may be used to search for larvae (Antonelli and Campbell 1989). Soil cores search a smaller area, but removing several cores from a broad area allows for scouting across a larger zone.

A drench of water containing an irritating agent applied to production fields or to the removed sod test strip will bring larvae to the surface, which facilitates detection. Applications of insecticides such as the pyrethroid bifenthrin and the carbamate carbaryl, cause large larvae (third and fourth instar) to come to the soil surface where they are relatively easy to detect (Stahneke et al. 1993, unpublished data). Salt solution, hot water, Jeyes’ fluid, and orthodichlorobenzene also are reported as effective disclosing solutions (Jackson and Campbell 1975), but these treatments have been shown to damage turf. Successful application of this technique requires high soil moisture to allow adequate transport of solution through the soil. In addition, thick thatch may inhibit transport of disclosing solution. After application, affected larvae will move to the surface within as little as 30 min, however, it may take overnight before larvae are observed. Disclosing solutions should be used for presence–absence detection of larvae only; they have not been found to offer reliable estimates of larval density. If such disclosing drenches are used, it is essential to wear protective clothing, eyewear, and gloves.

Beyond initial scouting to determine the presence in and around production fields, scouting for larvae during harvest is critical. Whole or dissected larvae will be visible during the harvest process and are readily distinguished from other soil insects and earthworms. Visually inspect the soil surface during harvest. If larvae are present at the soil surface, there is a high probability they will also be present in the harvested sod.

**Damage Thresholds.** On native rangeland, a damage threshold was calculated at 1X10⁶ larvae per hectare (Maercks 1953, Blackshaw 1984). Depending on soil nitrogen levels or date of larval sampling, however, thresholds may range from 865,000–2.5 X10⁶ per hectare (French 1969, French et al. 1990, Blackshaw and Newbold 1987). Action thresholds across amenity turf systems are lower. In the PNW, a damage threshold of 160–270 larvae/m² is recommended for vigorous turf, whereas 100–140 larvae/m² is appropriate for less vigorous turf (Antonelli and Campbell 1989). In the NE, spring populations of third-instar *T. paludosa* at densities of 123–142 larvae/m² were not associated with visible damage in healthy home lawns, while densities of 753–829 larvae/m² were (Peck et al. 2010). Producing a certified sod crop will depend on ensuring sod is free of invasive crane fly pests, therefore, detecting larvae in fields should result in treatment even when larval detection levels are below damage threshold levels. For noncertified crop, customer tolerance thresholds for insects in sod products should be driven by tolerance to other soil insect pests, such as white grubs. Both certified and uncertified sods...
need an additional safeguard when it is shipped beyond the known range of invasive crane fly establishment. In this case, a zero tolerance should be adopted because transport of this commodity may facilitate the spread of an invasive insect.

*Cultural Management.* As conditions that favor sod growth and vigor also favor larval survival, cultural control measures are not intended to completely eliminate crane flies from fields. Instead, these controls can diminish the capacity of sod fields and shipments to sustain invasive crane fly populations by modifying the conditions of the sod environment.

Controlling invasive crane flies in sod production starts by managing the areas surrounding the fields. If permanent grassy habitats adjacent to production fields are infested with invasive crane flies, adult flies will migrate from the grassy areas into the fields to deposit eggs. If scouting detects crane flies in these areas, it will be necessary to follow recommendations for curative actions in amenity turf.

As mentioned previously, high crane fly infestation rates in turf are associated with high soil moisture. Turf that remains in permanently saturated soils is at the greatest risk. Effectively draining saturated areas of fields and turf areas surrounding fields will decrease favorability to infestation. Conversely, in drier fields awaiting irrigation, delaying irrigation until after the time of egg deposition in spring (*T. oleracea*) or autumn (*T. paludosa*) can reduce the survival of eggs and larvae, as the early developmental stages of invasive crane flies are especially prone to desiccation (Maercks 1941; Laughlin 1958, 1967; Milne et al. 1965; Meats 1967, 1972). This should not be done, however, if withholding of irrigation poses a risk to the health of developing sod.

After harvest, maintaining sanitary fields and field edges are key in keeping pest populations below damaging levels. Ensure that all sod is harvested or removed from the field after harvest. Between sod crops, the soil of production fields should be turned by plowing or disking. Avoid disking under old sod fragments, as this will leave a food source for any remaining larvae. Removing the grass food source and altering the soil environment in this way can significantly help control insect pests (Cockerham 2008).

*Chemical and Biological Control.* Before deciding to intervene with insecticidal (chemical) treatments, the relative abundance of larvae within infested production fields should be considered. Action thresholds, as determined through in-field scouting, have been established to act as a guideline for keeping insect numbers below economically damaging population densities. For certified sod, treatment will be warranted if larvae are detected in production fields. With respect to direct damage to sod, thresholds similar to those for pasturelands or amenity turf are appropriate. If consumer tolerance to insect presence is low or shipments are being transported outside the current range of either invasive crane fly species, additional insecticidal treatments may be warranted (Table 1).

Several active ingredients are effective for invasive crane fly management; best results are obtained if applications are timed with respect to the crane fly’s life cycle. The two main windows for insecticidal control are late autumn and spring, which represent preventive and curative control approaches, respectively (Stahnke et al. 2005, Peck et al. 2008).

In New York there are >120 products registered for the control of invasive crane fly larvae in sod production. These include botanicals (e.g., azadirachtin); microbials (e.g., *Beauveria bassiana* Balsamo); pyrethroids (e.g., bifenthrin); carbamates (e.g., carbaryl); organophosphates (e.g., chlorpyrifos); neonicotinoids (e.g., imidacloprid); anthranilic diamides (e.g., chlorantraniliprole); and dual compounds (e.g., bifenthrin+carbaryl, bifenthrin+imidacloprid). Based on the results of efficacy trials conducted across western New York, southern Ontario, and the PNW, a wide range of products yield >70% control when targeting first and second instars of *T. paludosa*. Among them are bifenthrin (Stahnke et al. 2005, Peck et al. 2008), carbaryl (Peck et al. 2008), chlorpyrifos (Stahnke et al. 2005), chlorantraniliprole (Peck et al. 2008), imidacloprid (Stahnke et al. 2005, Peck et al. 2008); and the dual compounds bifenthrin+carbaryl (D. C. Peck, unpublished data) and bifenthrin+imidacloprid (Peck et al. 2008). These products are effective as preventive treatments. When the larger third- and fourth-instar larvae of *T. paludosa* were targeted in the spring with curative applications, results among efficacy trials have been variable. Peck et al. (2008) found that no insecticides available for usage in New York State sod production offered >70% control; imidacloprid provided the best results (60–64% control). Simard and Dionne (2002) reported 68–91% control with carbaryl. The best results (>70% control) were obtained in the PNW with bifenthrin (Stahnke et al. 2005); carbaryl (Simard and Dionne 2002, Stahnke et al. 2005); and chlorpyrifos (Stahnke et al. 1993, Stahnke et al. 2005).

Biologically-based products have shown lower efficacy in both preventive and curative applications. Peck et al. (2008) reported good results (68–82% control) from two preventive trials conducted with the entomopathogenic fungus, *B. bassiana*; however, similar levels of mortality were not detected by Stahnke et al. (2005). Intermediate control (50–60%) is reported from several strains of entomopathogenic nematodes (Stahnke et al. 1993, Peters and Ehlers 1994, Simard et al. 2006), but one trial yielded 95% control with *Heterorhabditis heliothidis* (Khan, Brooks and Hirschmann) (Finney and Bennett 1984).

*Monitoring Harvest and Beyond.* Even with diligent scouting and IPM implementation, larval detection may not occur until harvest (Table 1). At this point growers must consider sod certification, customer thresholds, and the eventual destination of harvested sod. For certified sod, insecticidal rescue treatments will be required if infestations are detected at harvest. If sod is to be shipped beyond the current range of either species or a low tolerance threshold exists, sod remaining in an infested field should be treated with a fast-acting insecticide. If sod from an infested field is inadvertently transported to the customer and installed before detection, information on insecticidal control should be transmitted to customers at the installation site. A recommended insecticidal rescue treatment for the consumer should be twofold: a fast-acting treatment to the newly installed sod followed by a preventative application at the time of adult emergence.

**Conclusion**

Invasive crane flies have the potential to cause damage to sod production in the northeastern United States. The BMPs provided here (Table 1) will reduce the capacity of production fields to hold damaging larval populations and guide the producer in cases where there is in-field pest detection. Response of consumers to invasive crane fly detection after sod delivery has shown that tolerance thresholds are low. The protocols stated here, including understanding invasive crane fly life history and ecology and informed intervention approaches, are provided to safeguard sod producers and their customers in the northeastern United States. When implemented, they will help to deter in-field damage and prevent the transport of invasive crane flies in sod shipments.

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