Face Fly (Diptera: Muscidae)—Biology, Pest Status, Current Management Prospects, and Research Needs

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Abstract

Native to Europe and Central Asia, face flies (Musca autumnalis De Geer, Diptera: Muscidae) were unintentionally introduced into North America and became pests of pastured beef cattle, dairy cattle, and horses. Female and male flies use their sponging proboscis with preustumal teeth to feed around moist, mucus membranes of an animal’s face and other body parts. While feeding, face flies agitate livestock and elicit defensive behaviors (e.g., ear flapping, head shaking and batting, hiding in deep shade, and adjustment of grazing), and they can transmit eye-inhabiting nematodes and pathogenic bacteria that cause pinkeye. Face flies can be partially controlled with feed-through insecticides that prevent development of face fly maggots in fresh cattle dung pats. Adults can be partially controlled with repellents and insecticides applied directly to animals. Trap-out tactics can be effective and may involve sticky traps placed around high animal traffic areas, such as waterers and feeders in pastures, dairy entryways, or wherever else livestock congregate in pastures. A review of the insect biology and life stages, physical and economic damages, surveillance strategies, and management options for the face fly is presented.

Key words: Musca autumnalis, pest profile, review, livestock, bovine pinkeye

Description of Life Stages and Life Cycle

Adult face flies are 6–10 mm long, with a gray thorax marked with four longitudinal black stripes. Both sexes have sharply curved M1 wing veins, and sponging mouthparts held up under the head when at rest (Fig. 1). The compound eyes of males meet at the vertex, and their abdomens are yellow on the sides, starting at the second segment, with a black stripe down the middle. Eyes of females have a wider vertex, and their abdomens are mottled gray-black all over, except for the first abdominal tergite, which has yellow patches at its lateroventral margins.

Face flies are holometabolous with active larval and adult stages and inactive egg and pupal stages. Females mate once in their lifetime and then fertilized eggs are laid singly into cracks and crevices of fresh (0–1 d old) bovine dung pats in batches of 7–36 (Fig. 2) (Teskey 1960, 1969). Gravid females avoid older dung pats and aged manure mixed with other barnyard debris. Face flies lay eggs almost exclusively in cattle dung, but other occasional substrates include horse, pig, and human dung, though these latter substrates are unsuitable for larval development (Teskey 1969). Larvae burrow into the moist dung and then feed by filtering bacteria, yeast, and small organic particles from the dung fluid. At maturity, lemon-yellow colored third instars (Fig. 3) disperse from their natal pat, burrow into the surrounding soil, and eventually pupate inside of puparia that become calcified and turn white with age (Fraenkel and Hsisao 1965; Darlington et al. 1983, 1984, 1985; Burt et al. 1992). Males emerge 1–2 d before females. Both sexes feed on plant nectar and dung, but females predominate on cattle and horses, where they feed mainly on tears, mucus, saliva, amniotic fluid, vaginal discharges, milk, and blood (Fig. 4) (Teskey 1960, 1969).

Face flies can be confused with house flies (Musca domestica Linnaeus, Diptera: Muscidae); the only other species of Musca in the New World at present. Vockeroth (1953) provided a key to distinguish males and females of the two species. Briefly, adult house flies have fine setae on the prepleuron, just ahead of the prothoracic spiracle. House fly larvae are smooth, creamy-white maggots, and they do not occur in less than 3-d-old cattle dung pats. House fly pupae range from amber through red to dark brown as they mature. Cluster flies (Pollema rudis Fabricius, Diptera: Polleniidae) can be confused with overwintering face flies in buildings, but are distinguished by crinkled, golden hairs on the thorax.

Developmental times vary with temperature, moisture, and food availability. Total egg-to-adult development time is 192 degree-days above 10.2°C (Moon 1983), and time from emergence to first oviposition requires another 70 degree-days above 11.8°C (Moon 1986). Egg-to-egg (F1–F1) can take as many as 62 d at 15°C, and as
few as 11 d at 35°C, though all life stages will cease development if temperatures are below their developmental temperature threshold (11.8°C). Depending on weather, numbers of generations per year can range from 3 to 4 in northern latitudes to as many as 12 in their southern range. Significant face fly mortality occurs in the immature stage before they reach the adult stage (Valiela 1969). Heat, dry weather, and predatory beetles kill eggs and larvae, competition with other dung feeding insects also kills larvae, and parasitic beetles and wasps kill larvae and pupae (Valiela 1969). Mortality is greater where dung is dry (Bay et al. 1969, Meyer et al. 1978a) and cattle are fed a grain-rich diet (Meyer et al. 1978b, Grodowitz et al. 1987). The average female face fly lives 11 d as an adult, and can complete 2–3 gonotrophic cycles (Krafsur and Moon 1997).

In late summer and early autumn, newly emerged adults and develop into a state of diapause by growing their fat body and ceasing development. This facultative diapause occurs when they experience cool temperatures and shorter photoperiods earlier as larvae and pupae (Stoffolano and Matthysse 1967, Valder et al. 1969, Read and Moon 1986, Krafsur and al 1999, Fowler et al. 2015). Diapausing adults are not attracted to host cattle; rather, they feed only on flowers and other extra floral sugar sources (Teskey 1969). During the onset of diapause, both sexes aggregate on sunny sides of natural and man-made structures and work their way into cracks and crevices where they eventually spend the winter. Adults shelter in areas such as attics, lofts, and tree cavities, or even potentially below the ground or ice, until temperatures are consistently warm enough to draw them out anew in the spring (Krafsur and Moon 1997). In spring, survivors emerge and mate, females find and feed on hosts, and eventually oviposit to begin the next grazing season’s population (Krafsur et al. 1999, b). Diapausing flies can survive fluctuating temperatures of −8 to 8°C for months as opposed to weeks in non-diapausing flies (Rosales et al. 1994). Additionally, diapausing flies can survive
sub-zero temperatures for a few hours as opposed to a few minutes in non-diapausing flies (Rosales et al. 1994).

**Geographic Distribution**

Face flies are native to Europe and Central Asia but were discovered in the 1950’s in Nova Scotia and New Jersey (Vockeroth 1953). It is reported the North American population was discovered in Nova Scotia and likely originated from western Europe (Bryant et al. 1981, Krafsur and Black 1992, Cummings et al. 2005). Since its discovery, populations established and spread west across North America (Krafsur and Moon 1997), and are now a concern to cattle and horse owners from New England through the Pacific Northwest, and to a southern limit at approximately 35°N (Fig. 5). Current explanations for the lack of face flies in the southern United States (e.g., Florida, Texas, southern California) include host distribution and climate, but neither explanation truly explains this phenomenon (Krafsur and Moon 1997).

**Effects on Host Animals**

Face flies cause direct and indirect damage as well as peripheral effects to host cattle and horses (Williams 2009). Direct damage results from contact between a pest and its host and includes direct injury to skin and other host tissues through bites, allergies or myiasis, as well
Table 1. Pathogens transmitted by the face fly along with associated disease, symptoms, hosts, locality, and effects

| Common name                      | Scientific name                      | Pathogen(s)                                      | Symptoms                                                                 | Host(s)                      | Locality                        | Untreated effects                  |
|----------------------------------|--------------------------------------|--------------------------------------------------|--------------------------------------------------------------------------|------------------------------|----------------------------------|-------------------------------------|
| Brucellosis<sup>a</sup>          | Brucellosis                          | *Brucella abortus* (Schmidt) Meyer & Shaw        | Profuse sweating, fever, joint/muscle pain                              | Cattle Fetuses              |                                   | Abortion, Arthritis                 |
| Eyeworms<sup>b</sup>             | Bovine and Equine Thelaziasis        | *Thelazia guosa* Railliet & Henry                  | 'Worms' infesting tear ducts and eyes, IBK-like symptoms                | Cattle and Horses           | North America                     | IBK                                 |
| Green-muscle Disease<sup>c</sup> | Hemorrhagic Bovine Filariasis        | *Parafilaria bovicola* Tabahashi                 | Dermal and subcutaneous lesions ('bleeding points')                     | Cattle                      | South Africa, Sweden, France,     | Death                               |
| IBR<sup>d</sup>                  | Infectious Bovine Rhinotracheitis    | Virus                                            | IBK-like symptoms                                                       | Calves; yearling cattle     |                                  | IBK                                 |
| Mastitis<sup>e</sup>             | Mastitis                             | *T. parva* (formerly *Corynebacterium*) pyogenes (Czapek) | Inflamed uter tissue (swelling, redness, hardness, pain)                | Lactating Cattle            |                                  | Pain; clotted, flaky, or watery milk; loss of teats |
| Pinkeye or IBK<sup>d,e</sup>     | Infectious Bovine Keratoconjunctivitis | *Moraxella bovis* M. bovocili Mycoplasma spp.     | Photophobia, corneal ulceration, opacity, and lacrimation               | Calves; yearling cattle     | World-wide                       | Temporary-permanent blindness; scarring |
| Allergens<sup>f</sup>            | Humans                               |                                                  |                                                                          | Humans                      |                                  |                                     |

Species author(s) and lettered journal references are listed in superscript above the species or common name.

<sup>a</sup>Krafsur and Moon (1997).
<sup>b</sup>Pickens and Miller (1980).
<sup>c</sup>Hall (1984).
<sup>d</sup>Brown et al. (1998).
<sup>e</sup>O'Connor et al. (2012).
<sup>f</sup>Moon (2019).
as behavioral and physiological responses to irritation (e.g., reduced fertility, growth, and lactation). Indirect damage results from diseases caused by fly-transmitted pathogens, such as bacteria and nematodes that cause eye injury and disfigurement. Lastly, peripheral effects result from increased pest management expenses that ultimately increase production costs, negatively affect non-target organisms, or result in policy changes and quarantines imposed by regulatory agencies.

Face flies cannot pierce skin, so they cannot feed on blood directly; however, their mouthparts have pre stomal teeth that can rasp, scrape, and penetrate the conjunctivae of host eye tissues triggering tear production (Broce and Elzinga 1984). Both sexes have sponging mouthparts that imbibe plant nectar and fluids from eyes, faces, and other body orifices. One to five face flies per eye per day can cause serious ocular lesions that mimic the symptoms of bovine pinkeye (Brown and Adkins 1972, Shugart et al. 1979). Such mechanical damage, whether sustained by face fly mouthparts, dust, weed, pollen, or excessive sunlight, predisposes the eye for infection, and increases epithelial discharges (Shugart et al. 1979, Arends et al. 1982). Fly feeding also prompts animals in pasture and rangeland to exhibit a variety of defensive behaviors, including head throws, tail flicks, and bunching together with their heads inwards to avoid attacking flies (Schmidtmann and Valla 1982, Woolley et al. 2018).

Besides being irri tant, face flies also transmit pathogens that indirectly damage beef and dairy cattle (Shugart et al. 1979; Berkebile et al. 1981; Gerhardt et al. 1981; Arends et al. 1982, 1984; Glass et al. 1982; Glass Jr. and Gerhardt 1984; Hall 1984; Cheville et al. 1989; Coleman and Gerhardt 1989; Johnson et al. 1991) (Table 1).

### Bacterial Transmission

The face fly mouthparts are particularly suited for sucking up fluids. The labellum is composed of a pair of labellar lobes covered with pseudotrachea (striations) to channel liquids into the oral opening surrounded by pre stomal teeth (Broce and Elzinga 1984). Surfaces of fly mouthparts, bodies, legs, and tarsi (or ‘feet’) can be contaminated with bacteria that remain viable for hours, and once ingested, up to 3 d in the fly alimentary tract (Glass et al. 1982; Glass and Gerhardt 1983, 1984). While the fly is capable of harboring bacteria, evidence suggests that the primary means of transmission is mechanical.

Infectious bovine keratoconjunctivitis (IBK), also known as pinkeye, is a common but preventable eye disease of cattle caused primarily by *Moraxella bovis* (Hauduroy), *M. bovoculi*, and *M. ovis* (Lindqvist) (Broce and Elzinga 1984, Hall 1984, O’Connor et al. 2012, Loy and Brodersen 2014, Angelos 2015). Clinical signs of IBK are excessive lacrimation, inflammation of the eye, conjunctival edema, corneal opacity, and ulceration (Postma et al. 2008, Alexander 2010, Angelos 2015). Animals with IBK may exhibit weight loss, impaired vision, eye disfigurement, and blindness. These gram-negative bacteria enter the eye using pilin proteins to attach to the eye and cytotoxins to erode the cornea. Commercial and autogenous IBK vaccines are promoted for disease prevention (Angelos et al. 2007, 2010). Some of these vaccines target the pilin protein attachment to the eye but are unable to effectively protect cattle from disease (Cullen et al. 2017, O’Connor et al. 2019). Both *M. bovis* and *M. bovoculi* have been isolated from bovine eyes in the absence of IBK symptoms, suggesting there are gaps in our understanding of these bacteria in the epidemiology of IBK.

Face flies transmit *M. bovis* by regurgitating droplets from the foregut and midgut, by externally contaminated mouthparts, legs, and tarsi (Steve and Lilly 1965, Berkebile et al. 1981, Glass et al. 1982, Glass and Gerhardt 1984). Although the face fly can spread *M. bovis* from animal to animal, the relatively short residency of the bacteria, as well as absence of the causative agent in the hemolymph, indicate that this species does not propagate in the fly (Glass et al. 1982). The pathogen does not overwinter in the fly, and the herd is the likely source of contamination (Steve and Lilly 1965, Alexander 2010). The prevalence of *M. bovis* in flies was shown to be 1–9% when detected with culturing techniques (Berkebile et al. 1981, Gerhardt et al. 1981), but it is likely greater with more sensitive and specific molecular methods currently available (Nayduch et al. 2019).

Economic losses associated with IBK include weight loss, culling infected animals, fly control, pinkeye treatment, labor costs, and reduced cattle prices for unthrifty animals (Sinclair et al. 1986). IBK-associated losses are estimated to exceed $150 million in beef and dairy systems and are prevalent in young cattle (Hansen 2001). Purebred Hereford and Angus X Hereford crossbred cattle, which have mostly white faces, are more susceptible to IBK than Brahman, Boran, and Tuli crossbreds (Snowder et al. 2003). Calves lose between 5 and 8 kg (2.2–17.6 lbs) and 16–29.5 kg (35.3–65 lbs) in singular and double-eye infections, respectively (Hall 1984), although single-eye infections are threefold more frequent (Slatter et al. 1982). These losses become significant, considering that 8–50% of farmers report having annual infections of herds (Cheng 1967, Harris et al. 1980, Webber and Selby 1981, Sinclair et al. 1986, Martin et al. 2019). To monitor bovine pinkeye, typical signs include excessive tears, excessive blinking, opaqueness, photophobia, lesions, and squinting or involuntary eye closure (Hall 1984, Brown et al. 1998). Figure 6 illustrates the progression of bovine pinkeye infection.

Brucellosis is caused by several strains of gram-negative bacteria in the genus *Brucella* (Rhizobiales: Brucellaceae) (Seleem et al. 2010). *Brucella abortus* (Schmidt) Meyer and Shaw is a blood-borne pathogen infecting cattle and humans. In cattle, *B. abortus* causes fetal abnormality and abortion, and there is no vaccine. Elk and
bison serve as reservoirs for *B. abortus* that can be spread to susceptible cattle. Prevention of brucellosis in cattle is key to limiting or preventing human infections (Corbel 1997). In cattle, *B. abortus* is shed from the mammary gland and is likely transmitted from cow to calf. When *B. abortus* was administered in a nutrient broth to face flies, researchers were able to recover the bacterium from flies for 12 h, but not more than 72 h after which the fly’s digestive enzymes neutralize the bacterium (Cheville et al. 1989).

Strangles, caused by the bacterium *Streptococcus equi* (Lactobacillales: Streptococcaceae) (Sand and Jensen), is an infection in the respiratory tract of horses. Mild forms of the disease result in nasal discharge and minor lesions that resolve quickly; whereas, severe cases cause suffocation resulting from the obstruction of the airways (Sweeney et al. 2003). Strangles is a highly communicable disease passed through close physical contact such as horse-to-horse, respiratory droplets, and fomites. The role of face flies as a vector of these bacteria has not been resolved. During a strangles outbreak in California these bacteria were detected in qPCR from face flies collected from that site, but 0.54% of flies were positive (Pusterla et al. 2020). This suggests that face flies can get infected, but is not sufficient to incriminate face flies in transmission of strangles (Pusterla et al. 2020).

**Nematode Transmission**

*Thelazia* eyeworms (Spirurida: Thelaziidae) are nematodes that infect the eyes of mammals, including humans, ruminants, equids, felids, and canids (Otranto et al. 2003, Otranto and Traversa 2005, Bradbury et al. 2018). They are cosmopolitan and found on nearly every continent. Non-biting flies serve as intermediate hosts and vectors. Face flies transmit *T. gulosus* Railliet and Henry, *T. lacrymalis* (Gurlt), and *T. skryjabim* Erschow in North America. A complete list of *Thelazia* species, their preferred hosts, known vectors, and geographic distributions can be found in Otranto and Traversa (2005) and additional information on *Thelazia* development in face flies is also available elsewhere (Geden and Sroffolano 1980, 1981, 1982). *Thelazia* L1, L2, and L3 larvae develop in their adult face fly host. The L3 larvae are transmitted to the animal host when an infected fly feeds on a host’s eyes. Adult eyeworms occur under eyelids and nictitating membranes and inside conjunctival sacs and lachrymal excretory ducts of the eye. Clinical signs of infection resemble mild cases of pinkeye, including lacrimal secretions, conjunctivitis, corneal opacity, and lesions on the eye and surrounding tissues. Within the United States, the four *Thelazia* spp. that occur in cattle and horses are exclusively transmitted by the face fly (Krafsur and Church 1985).

*Parafilaria bovicola* (Spirurida: Filariiidae) (Tubangui 1934) is a nematode that causes subcutaneous lesions on the backs and sides of cattle. The lesions ooze blood and serum containing the nematode’s L1 microfilaria, which attracts hungry face flies. Once ingested, the nematode develops from L1 to L3 in the face fly hemocoel and fat body (Bech-Nielsen 1982). Face flies and close relatives transmit *P. bovicola* among cattle in Europe, northern Africa, Middle East, southern Asian, and south Africa, where the nematode is endemic. The nematode has been identified in Europe from Austria, Belgium, the Netherlands, Germany, Italy, Bosnia, and Herzegovina, where isolated occurrences are managed either by euthanasia or ivermectin treatments (Borgsteede et al. 2009, Hamel et al. 2010, Galuppi et al. 2012, Stevanovic et al. 2014).

**Virus Transmission**

Face flies acquire animal viruses, but they appear to be dead-end hosts, with little or no transmission potential. For example, face flies can carry bovine viral diarrhea virus (BVD) and contaminate surfaces (Gunn 1993), but their role in transmission has yet to be investigated. Similarly, bovine herpesvirus-1 (BHV-1) administered in albumin to starved face flies did not persist beyond 48 h, nor was the BHV-1 virus transmitted to naive calves (Johnson et al. 1991).

**Economic Damage**

Peripheral effects associated with face flies on livestock include economic losses, quarantined animals, and reduced animal health and welfare. Annual losses in face fly control costs and lost animal production were estimated to exceed $52 million for U.S. range cattle (Drummond et al. 1967), which would be approximately $423 million in 2020 dollars (https://www.usinflationcalculator.com/). When *Parafilaria* was introduced in Sweden during the 1980s, losses were estimated at $8 million (≈ $13 million now) in meat and hide damages (Bech-Nielsen et al. 1983).

Other effects are more difficult to assess. Cattle increased the rate of dry matter intake as the number of face flies increased on animals (Dougherty et al. 1993); however, several studies assessed effects of face fly stress on dairy and beef cattle and failed to find substantial losses (Schmidtmann et al. 1981a, 1984; Arends et al. 1982; Schmidtmann 1985a; Schmidtmann and Berkebile 1985). While it remains challenging to measure the direct economic impact of face flies on cattle, the prevention of disease, especially pinkeye, is a strong incentive for producers to manage flies. In our experience, cattle producers are more concerned about pinkeye than face flies. While face flies can transmit bacteria that causes pinkeye (see below), the presence of face flies does not imply pathogen transmission, nor does their absence imply no transmission. This is why estimating pinkeye risk based on face fly numbers is problematic. Also, an indirect measure of fly pressure is animal behaviors: tail flicks, head tosses, flank switches, etc. In recent years, consumer groups have taken a proactive stand on animal welfare, focusing on livestock care, treatment, housing, and comfort (Barkema et al. 2015). The absence of large economic effects suggest an economic threshold for treatment is probably >15 flies per face (Krafsur and Moon 1997); however, expression of defensive behaviors suggests an annoyance threshold may be lower (Schmidtmann et al. 1981b; Schmidtmann and Valla 1982; Schmidtmann 1985a,b; Schmidtmann and Berkebile 1985).

**Traditional Management Strategies**

Extensive livestock production is an animal management system characterized by large areas of native or improved pastures that provide the sole food source for livestock during the growing season. Compared with intensive systems, extensive systems are generally lower in productivity per animal and per pasture area; but they utilize lower levels of external inputs, capital, and labor. Face flies are most common in extensive livestock product systems such as cow/calf and stocker animals housed mainly on pasture and rangeland.

Management strategies for face flies include insecticide ear tags, dust bags, oiler/rubs, pour-ons, sprays, feed-throughs, and air-projected capsules. Non-chemical control methods include walk-through traps, sticky traps, and conservation of beneficial insects such as predaceous dung-inhabiting beetles. Commercial and autogenous pinkeye vaccines are available and should be administered before animals are sent to summer pasture.

Organic livestock production systems integrate cultural, biological, and mechanical practices to foster a cycling of resources, promote an ecological balance, and conserve biological diversity. Within the organic system, according to the pasture rule, ruminants must be given daily
access to pasture and acquire 30% of their annual dry matter intake from pasture (Rinehart and Baier 2011). Consequently, organic and conventional cattle in extensive systems are likely to be more exposed to dung pat breeding face flies and horn flies (Haematobia irritans L.) than are dairy and beef cattle raised in conventional, dry lot-based intensive systems. Prevalence of face flies and the pathogens they transmit within conventional and organic systems has not been evaluated.

Face fly and pinkeye management are likely to be needed during summer in extensive production systems. Conventional producers may use traditional synthetic control products for face fly control (see below). Organic systems have a more restricted list of available essential oils and botanicals such as pyrethrins applied as sprays, ointments, or as a wipes. Diatomaceous earth may be used in dust bags in force-use or free-choice arrangement, but efficacy against face flies is questionable. If a pasture is rather small, a mechanical option for control of face fly (and horn fly) larvae could be to disrupt the pasture at 1–3 d intervals to break apart the dung pats and stop larval development. Before using any ectoparasite control product on a certified or transitional farm, organic certifiers should be consulted (e.g., FDA National Organic Program).

Monitoring Methods
Few monitoring methods are used to assess face fly populations on cattle or horses. Normally, the producer visually inspects the animal, and if the animal ‘has flies’, or shows signs of irritation, then flies on those animals are considered problematic. Early on, monitoring face flies typically consisted of visual observations of flies on animals’ faces (McGuire and Sailer 1962, Hansens and Valiela 1967). Researchers would count the number of flies on the faces of 15 animals within a herd (Ode and Matthyssee 1967). More recently, photography has been used to document numbers of face flies, and animals within a herd (Ode and Matthysee 1967). More recently, more effective in trapping other fly species like face flies and stable flies. An alternative trap is a fly vacuum system available commercially (CowVac, Spalding Laboratories). Instead of passive fly collection, disturbed flies are sucked by vacuum into a cage. The FlyVac was developed for controlling horn flies, but also will capture face flies and stable flies (Denning et al. 2014); however, others found that the vacuum system only controlled horn flies and that face and stable fly populations were not reduced (Kienitz et al. 2018). Further, dairy herd productivity and discomfort behaviors did not change when traps were activated.

Cultural Control
Cultural control methods for face fly control are often not practical simply because methods involve too much effort or simultaneously destroy pastures. Confined cattle systems with trampled dung rarely have face fly populations unless they are emigrating from other locations. If dung pats in pasture systems are too wet, larvae will desiccate because tunnels made for airflow will collapse. Drying dung pats or those that dry quickly after being spread will desiccate horn fly larvae (McLintock and Depner 1954); so it can be speculated that face fly larvae will be desiccated as well. Thus, spreading or inundating dung on pastures by dragging or flooding is possible, but again it will likely damage the pasture or it is simply not practical.

Conservation Biological Control
Biological control results from activities of beneficial organisms that kill target pests (Drummond et al. 1988a, Darwish et al. 1990, Fincher 1990, Rutz and Scott 1990). A rich fauna of predators, competitors, parasitoids, and entomopathogenic organisms occur naturally in pasture habitats. Livestock producers can conserve those beneficial organisms by avoiding use of broad-spectrum insecticides and anthelmintics at times when those beneficial organisms are active, which is generally during the growing season. Like cultural control methods, the utility of buying and using these agents for face fly control is not practical for most producers.

Predators
Beetles in the families Carabidae, Histeridae, Staphylinidae, and Hydrophilidae and mites in the family Macrochelidae are generalist predators that feed on immature face flies and other dung inhabiting Diptera (Turner et al. 1968, Valiela 1969, Kessler and Balsbaugh 1972, Campbell and Hermansen 1974, Wingo et al. 1974, Legner 1978, Thomas et al. 1983, Drummond et al. 1988a). While the impact of predators on face fly populations is not well understood, their benefits can be conserved by avoiding the use of broad-spectrum macrocyclic lactones (Table 2) in spring and summer, when populations of naturally occurring beneficial insects are increasing (Floate 2006).
Table 2. Insecticides and modes of action proposed for adult and larval face fly control, in historical order of appearance in the literature

| Chemical ([IRAC Group No.]a) | Primary site of action            | Target life stage | Delivery methods                                                                 | References                                                                                      |
|-----------------------------|-----------------------------------|-------------------|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| Organophosphates (1B)       | Acetylcholinesterase Inhibitors    | Adult, Larval     | Dusts, ear tags, oil/rub, feed-through, air-projected capsule                     | Casida (1956); Kearns (1956); O’Brien (1963, 1966); Thompson (1999)                               |
| Natural pyrethrum (3A)      | Sodium channel Modulator          | Adult             | Sprays                                                                            | Sun and Johnson (1960), Cox (2002), Arnason et al. (2012), Ghosh and Ravindran (2014)           |
| Benzoylureas (15)           | Inhibitors of chitin Biosynthesis, type 0 | Larval            | Feed-through                                                                     | Miura et al. (1976), Grosscurt (1978), Mayer et al. (1980), Matsumura (2010)                     |
| Pyrethroids (3A)            | Sodium channel modulator          | Adult             | Dusts, ear tags, pour-ons, sprays, oils/rubs, air-projected capsule               | Elliott and Janes (1978), Vijverberg et al. (1982), Casida et al. (1983), Coats (1990)          |
| Avermectins (6)             | Chloride channel Activator        | Adult             | Ear tag, air-projected capsule                                                   | Campbell (1981), Bloomquist (1996), Martin (1997), Geary (2005), Lynagh and Lynch (2012)        |
| Neem, azadirachtin (uncertain) | Anti-feedancy, growth regulation, fecundity suppression and sterilization | Larval            |                                                                                    | Gaaboub and Hayes (1984a,b); Mulla and Su (1999)                                                 |
| Essential oils* (uncertain) | Neurotoxic, neuromodulator octopamin, GABA-gated chloride channels | Adult             | Sprays                                                                            | Isman (2006), Cloyd et al. (2009); Khater (2012)                                                 |
| Tolfenpyrad† (21A)          | Mitochondrial complex I electron transport inhibitor (METI) | Adult             | Ear Tag                                                                           | Commercial launch                                                                                   |

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*aSee Nausen et al. (2019) and access www.veterinaryentomology.org for a list of labeled fly control products.

bwww.irac-online.org.

*Minimum risk pesticides exempt from Environmental Protection Agency registration under Section 25b of the Federal Insecticide Fungicide Rodenticide Act.

†The different compounds in this mode of action group (21A) belong to several different chemical classes. Tolfenpyrad is a pyrazole insecticide.
Competitors

Dung beetles and dung feeding flies can compete with face fly larvae for fresh dung. Scarab beetles (Scarabaeidae) in different subfamilies can shred, disperse, and bury dung within days of dung pat deposition. In the process, those beetles can damage fly eggs and larvae directly, and reduce dung supply and quality for fly larvae and gastrointestinal parasites (Nichols 2008). Other large dung feeding Muscidae, Anthomyiidae, Sarcophagidae, and Scathophagidae may reduce face fly larval success (Valiela 1969, Moon 1980, Fowler and Mullens 2016).

Parasitoids

Species in five families of parasitic Hymenoptera and one family of Coleoptera have been reared from face flies in bovine dung in North American pastures (Blickle 1961, Benson and Wingo 1963, Sanders and Dobson 1966, Burton and Turner 1968, Thomas and Wingo 1968, Turner et al. 1968, Wylie 1973, Wingo et al. 1974, Figg et al. 1983, Moon and Cervenka 1991). Two commonly encountered species are braconid larval-pupal endoparasitoids; Aphaereta pallipes (Say) is a gregarious species and Abyssia species are solitary. The remaining four are solitary pupal parasites, a cynipid, Eucoilia impatiens (Say), a figitid Xyalophora quinquilineata (Say), and two pteromalids, Spalangia nigra Latrelle and Muscidifurax raptor Girault and Sanders. Most of these parasitoids are generalists that also attack pupae of dung inhabiting muscid, anthomyiid, and sarcophagid flies. While these wasps are geographically widespread, they cause far lower levels of apparent mortality in the introduced face fly (<10%) than among other dung-breeding flies, which are indigenous to North America (Turner et al. 1968, Hayes and Turner 1971). Interestingly, A. pallipes is notably unable to exit a face fly's calcified puparium, and the other wasp species have difficulty locating face flies that have dispersed from dung pats into the surrounding pasture habitat.

In North America, five Aleochara (staphylinid) dung-inhabiting species were reared from exposed face fly puparia (Klimaszewski 1984, Maus et al. 1998, Bezanson and Floate 2019). Aleochara females lay their eggs in and around dung pats, where free-living larvae hatch and then penetrate host fly puparia, including face fly pupae that have pupated away from the natal pats. The beetle first instars develop within the puparia next to the pupae proper. The adults then emerge from the puparia and feed on eggs and larvae of cyclorrhaphous flies. Aleochara parasitism is typically <5% in face flies because these beetles also parasitize other dung-breeding flies (Thomas and Wingo 1968). In Europe, A. tristis Gravenhorst was tested as a biological control agent against face flies (Jones 1967, Heller 1976). Although A. tristis established, it could not increase face fly mortality (Klimaszewski and Cervenka 1986). While mass-rearing and storage methods were developed for A. bilineata (Gyllenhal) on Delia antiqua (Meigen) (Whistler craft et al. 1985), it remains unknown if these methods could be used for A. tristis in an augmentative control program for face flies.

Entomopathogenic Viruses

Salivary gland hypertrophy virus (Hytrosaviridae) infects house fly, tsetse fly (Glossina spp., Diptera: Glossinidae), and narcissus bulb fly (Merodon equestris (F.), Diptera: Syrphidae) (Geden et al. 2011). The virus is likely transmitted from fly-to-fly contact through co-feeding food sources or through environmental contamination as was previously reported in house flies (Lietze et al. 2007, Geden et al. 2008). Infections reduce fecundity, inhibit ovarian development, and reduce male mating success (Lietze et al. 2007). Laboratory transmission studies indicated salivary gland hyper trophy virus could infect face flies as well as stable flies (Stomoxys calcitrans L.), black dump flies (Hydrotæa aemensæ) Wiedemann), and a flesh fly (Geden et al. 2011).

Entomopathogenic Bacteria

Early studies with Bacillus thuringiensis (Bt) using exotoxin-producing Bt strains against filth flies, such as the house fly, offered encouraging results (Burns et al. 1961, Miller et al. 1971, Carlberg 1986, Rupes et al. 1987). Bacillus thuringiensis was evaluated as a feed additive, and it effectively reduced face fly development (Hower and Cheng 1968); however, safety concerns about vertebrate toxicity in the 1980s prohibited the use of exotoxin-containing Bt products in the United States (McClintock et al. 1995). Strains of Bt lacking exotoxins (exotoxin-free strains) were identified (Choi et al. 2000, Labad and Rady 2001, Oh et al. 2004), but these exotoxin-free strains have not been assayed against face fly larvae.

Entomopathogenic Fungi

Beauveria bassiana (Balsamo-Crivelli) Vuillemin and Metarhizium anisopliae (Metschnikoff) Sorokin, were evaluated against house fly larvae and adults and stable fly larvae under laboratory conditions (Hall et al. 1972, Barson et al. 1994, Geden et al. 1995, Watson et al. 1995, Angel-Sahagun et al. 2005, Lecuona et al. 2005, Kaufman et al. 2008, Weeks et al. 2017). Steenberg et al. (2001) reviewed the entomopathogens in Denmark and found a low natural presence of B. bassiana and Entomophthora muscae (Cohn) Fresenius in field-collected face flies (Steenberg et al. 2001). Additional experimental studies should be conducted to determine entomopathogen efficacy at controlling face flies.

Entomopathogenic Nematodes

Entomopathogenic nematodes have been studied extensively for effects on face flies. Parasiotochium autumnale (Nickle) (= Heterotylenchus autumnalis) was identified as a natural control option for face flies because it sterilizes females. The potential for H. autumnalis to control face flies was identified (Stoffolano and Nickle 1966, Stoffolano 1970, Thomas et al. 1972, Kaya and Moon 1978, Kaya et al. 1979, Krasuf et al. 1983, Chirico 1990, Soto et al. 2014), but applications at the commercial scale have been limited by inability to mass produce and distribute nematodes into face fly infested pastures and rangeland. The nematode, P. autumnale, is naturally found in 10–20% of face fly adults, with occasional reports of parasitism rates being >50% (Briggs and Milligan 1977, Soto et al. 2014). Once mated, female nematodes burrow from dung fluid into the larval face fly cuticle and then live inside the fly during the rest of the fly’s life. In the female face fly, the female nematode produces asexual nematodes that invade the ovaries. The infected fly will then lay nematodes (”nemaposit”), as if ovipositing (Stoffolano 1970, Soto et al. 2014). Further research indicated that nemaposit could not control the entire face fly population (Kaya et al. 1979, Soto et al. 2014). Instead, P. autumnale could stop cyclical protein feedings as infected face flies feed on dung rather than blood or other animal secretions; thereby, preventing or limiting the second gonadotrophic cycle and sterilizing the flies (Kaya and Moon 1978).

Chemical Control

Insecticides applied via ear tags, as sprays, and pour-on and feedthrough products are used to manage face flies. Various modes of
action are available for face fly management and control (Hall and Foehse 1980; Herald and Knapp 1980; Pickens and Miller 1980; Williams and Westby 1980; Miller et al. 1981, 1986, 1991; Knapp and Herald 1981, 1982, 1983, 1984; Miller, Hall, et al. 1984; Krafsur 1984; Knapp et al. 1985; Hogsett and Ruff 1986; Scott et al. 1986; Broce and Gonzaga 1987; Skoda et al. 1987; Moon et al. 1991; Miller and Miller 1994; Nauen et al. 2019). Compounds with various modes of action are available at the VeterinaryPestX database (https://www.veterinaryentomology.org/vetpestx) (Gerry 2018) and include avermectins/milbemycins (group 6), benzoylureas (group 15), organophosphates (Group 1B), juvenile hormone analogs (Group 7A), and synthetic pyrethroids (Group 3A) (Table 2). These materials are applied as air-projected capsules, dusts, feed-throughs, injections, insecticidal ear tags, pour-ons, and sprays. For more information about the Insecticide Resistance Action Committee (IRAC) codes, visit www.irac-online.org. Current recommendations involve alternating compounds with different modes of action, i.e., alternating to a compound with a different IRAC code from the one used in the preceding year.

Feed-through insecticides include larvicides and insect growth regulators (IGRs) that animals consume with feed or minerals, and are eventually excreted in manure. Female flies ovipositing in treated manure exposes immatures to a treatment that either kills them or arrests their development. The active ingredients dibenzuranon, tetrachlorvinphos, and methoprene kill face fly larvae (Miller and Uebel 1974, Pickens and DeMilo 1977), although not all are available in every state. Efficacy for individual herds may be limited by face fly dispersal, as adult flies will move from neighboring herds where feed-through products are not used (Pickens and Miller 1980). Feed-throughs could be valuable if used in area-wide control programs enough to reduce the effects of migration.

Off-target impacts associated with feed-through insecticides include effects on non-target populations (Cook and Gerhardt 1977, Fincher 1991). Feed-through formulations are administered to cattle continuously, and efficacy depends on the animal consuming the correct amount of additive daily: too low allows immatures to survive and too high can have non-target effects. Nevertheless, the label instructions should always be followed.

Avermectins/milbemycins (macrocyclic lactones or MLs, group 6) are closely related 16-membered ML derivatives produced through fermentation by soil-dwelling Streptomyces. Common veterinary MLs include abamectin, doramectin, eprinomectin, ivermectin, selamectin, and milbemycin oxime. Avermectins bind at gamma-aminobutyric acid (GABA) receptors in the nervous systems of insects and nematodes, thus blocking electrical transmission between nerves and muscle cells, which leads to hyperpolarization and subsequent paralysis of neuromuscular systems (Bloomquist 1993, 1996). MLs are not labeled for face fly larval control, but a study using ivermectin excreted from cattle dung (applied via subcutaneous injection or via pour-on to the animal) demonstrated that dung with ML reduced survival of face fly larvae for 14 to 28 d post-treatment (Sommer et al. 1992).

Use of MLs in livestock is a concern from an ecotoxicological standpoint. Persistence of MLs in manure of treated cattle may harm invertebrates that are important for manure pat degradation and nutrient recycling into soil (Floate 2006). Effects vary among MLs, their formulations, and susceptibility of insect species in treated areas (Floate et al. 2005).

Abamectin ear tags were introduced in the early 2000s and provided an alternative to organophosphate and synthetic pyrethroid insecticide ear tags. A combination ear tag combining abamectin, a synthetic pyrethroid, and piperonyl butoxide was introduced in the late 2000s and reduced face fly numbers on tagged cattle by 70% over 6 wk (Boxler, unpublished).

Benzoylureas (group 15) inhibit chitin biosynthesis and have been used against the face fly as feed-throughs (diflubenzuron) (Pickens and DeMilo 1977; Miller et al. 1986, 1991).

Organophosphates (OPs) (Group 1B) intoxicate insects and mammals by inactivation of the enzyme acetylcholinesterase (Fukuoto 1990). Application options for OP insecticides include dusts, feed-throughs, insecticidal ear tags, oilers/rubs, and sprays. Self-treatment devices such as dust bags and oilers/rubs commonly used by livestock are often positioned near water stations or mineral feeders for use on a ‘free-choice’ basis. Forced daily use would be better.

Currently, two emulsifiable concentrate OP products, Phosmet and Co-Ral, are labeled for direct animal application, but both carry age application restrictions. Presently, there is one organophosphate, tetrachlorvinphos, used as a feed additive that is typically incorporated into mineral blocks or added to mineral or feed.

Synthetic pyrethroids (Group 3A) are insecticides that delay closing of the voltage-sensitive sodium channel leading to death; in some instances, causing uncontrolled, uninterrupted nerve firing. Synthetic pyrethroid insecticides for face fly control are formulated as dusts, pour-ons, sprays, ear tags, and air-projected capsules. Synthetic pyrethroid insecticides have been used by livestock producers since the early 1980s (EPA 738-F-06-012, June 2006).

Natural Products/ Bio-pesticides

Pyrethrum is probably the most widely used botanical insecticide worldwide. The flowers of chrysanthemum, Tanacetum cinerariifolium Schultz and Bipinnatus, are ground into powder and extracted using solvents (Casida and Qustad 1995). Two natural pyrethrum compounds from another plant, Chrysanthemum cinerariifolium (Treviranus), are neurotoxic to insects (Yang et al. 2012). Pyrethrum and pyrethrins are contact insecticides, and their mode of action is a result of neurotoxic action, which block voltage-gated sodium channels in nerve axons, which affects face flies in the exact same method as pyrethroids (Duke et al. 2010). Pyrethrum and pyrethrins were initially applied as synergized animal sprays, but studies reported short-term to no effect on face fly populations because these compounds act as a repellent and face flies spend very little time on their host (Granett and Hensans 1961, Ode and Matthysse 1964, Poindexter and Adkins 1970). Poor results may be due to pyrethrins being very unstable in UV conditions and heat, which limits the areas where they are effective (Casida 1980).

Neem (azadirachtin) is derived from a group of plants from the family Meliaceae that grow in India, Africa, Central and South America, China, Vietnam, and Thailand. Neem can have multiple effects in insects, including antifeedancy, growth regulation, fecundity suppression, sterilization, oviposition repellant, and other changes in biological fitness (Mulla and Su 1999). Azadirachtin at low concentrations caused 11 % mortality to third instar face flies, and subsequent adult numbers were reduced by 52% by interfering with pupal formation and adult emergence (Gaaboub and Hayes 1984a,b).

Essential oils are mixtures of volatile extracted plant compounds that include various alcohols, terpenes, and aromatic compounds (Khat 2012). Many essential oils are bioactive against a variety of arthropod pests of crops (Cloyd et al. 2009). Daily applications of lemongrass and geranium essential oils or mixtures to organic dairy cattle were evaluated and researchers observed lower face fly
densities, reduced cattle defensive behaviors, and increased grazing times compared with untreated animals (Woolley et al. 2018).

Genetic Modifications of Face Flies
Use of genetic technologies (e.g., gene-drive, genetic editing) to manage face fly populations has been considered. Knowing that face fly diapause is a heritable trait that also responds to environmental factors (Kim et al. 1995), it was suggested as a potential genetic mechanism for management (Geden and Hogsette 1994). This is because temperature and day length induce diapause and the rate of fat body hypertrophy is temperature-dependent (Stoffolano and Matthysse 1967, Valder et al. 1969, Caldwell and Wright 1978, Read and Moon 1986, Evans and Krafsur 1990). The use of radiation to control face flies was evaluated by inducing a dominant lethal mutation that killed sperm; however, treatment of males did not affect insemination rates or eclosion, and fecundity and fertility were determined to be inversely proportional to the radiation dose (Mansour and Krafsur 1991). Mansour and Krafsur (1991) did speculate that local eradication could be possible with coordinated releases. Future research should include sequencing and annotating the face fly genome in order to develop, evaluate, and validate additional genetic modes of management as well as the role that epigenetics has in diapause.

Genetic Modifications of Host Animals
Few studies have addressed host tolerance and host resistance to face flies. We define pest tolerance as an animal that is not bothered or affected by the feeding of face flies and may not have fly-associated losses. Conversely, pest resistance is the idea that some hosts are not a preferred host to face flies and rarely have flies on them. Researchers identified darker haired cattle with more face flies compared with white or Holstein cattle (Engroff et al. 1972), but these findings have not been repeated (Teskey 1960, Schmidtmann and Berkheile 1985, Steelman et al. 1993b). Damage caused by face flies, transmission of pinkeye, and microlacerations on eyes, vary by breed. Susceptibility to pinkeye infection was most prevalent in Angus, Herefords, Shorthorns, Jerseys, and Friesians (Steelman et al. 1993a). Additionally, there are reports that tropical cattle breeds (Bos indicus Linneaus) are more resistant to pinkeye infection than temperate breeds (Bos taurus Linneaus) (Slatter et al. 1982b, Snowden et al. 2005). Light-skinned animals, such as Jerseys, Guernseys, Friesians, and especially Herefords, are more pinkeye-prone (Webber and Selby 1981, Slatter et al. 1982b, Sinclair et al. 1986, Steelman et al. 1993b, Snowden et al. 2005). While there is much debate about whether face flies prefer certain colors over others (Steelman et al. 1993b), it's more likely because light-skinned tissue around the eyes is more sensitive to UV radiation—one of the causes of bovine pinkeye (Slatter et al. 1982a). Previously infected cattle become immune to clinical pinkeye symptoms, but also remain carriers of the same pathogens (Webber and Selby 1981, Brown et al. 1998). Older, immune cattle are reservoirs to the largest susceptible age group—the calves (Webber and Selby 1981, Slatter et al. 1982a, Sinclair et al. 1986). Calves are developing their bodies at the same time as their immune systems and so are often gravely affected by pinkeye; this explains the heterogeneity of pinkeye on farms as well as why calves are the largest group affected.

The Three I's: IPM, Immigration, and Insecticide Resistance
Integrated pest management (IPM) is highly recommended for face fly control because IPM uses multiple controls simultaneously to suppress pest populations (Moon 2019); however, using IPM tactics to control face flies is difficult and the problem is threefold. First, the most useful strategy is to eliminate dung (face fly development site), but this is difficult in pastures because of the space and time required to spread, dry, and/or bury dung. Second, while pasture may include a diverse group of biological agents, there are, unfortunately, no effective biocontrol agents of face flies commercially available at this time. Third, face flies spend limited time on their hosts and travel among herds (Morgan and Pickens 1979, Moon 2019). Thus, cattle producers implementing good face fly and pinkeye control could still see significant infections sourced from neighboring herds.

Because of these particular shortcomings, many farmers rely almost exclusively on chemical controls (e.g., ear tags, sprays, feed-throughs) to suppress face fly populations.Repeatedly exposing and killing most, but not all, face flies allows the survivors to develop resistance and pass it to their progeny genetically. In fact, face fly immatures exposed to insecticides intended for other arthropods or adults can develop resistance before they become adults. This problem is exacerbated when considering how else resistance might form. Face flies resistant to a particular insecticide within a class are more likely to develop resistance to insecticides with similar chemical structures in that class in a process known as ‘cross resistance’ (Axtell 1986). In general, face flies across the United States have shown resistance primarily to older insecticide classes, such as organochlorines (Drummond et al. 1988b). As of this writing, face flies have not been evaluated for insecticide resistance and this may be due to the fly's avoidance behavior spending little time on the host. We suspect that insecticide resistance varies from population to population because individual livestock producers may use different pesticides. Consequently, there is a need to evaluate face for insecticide resistance to different modes of actions.

Producers can slow resistance development by monitoring their fly populations, starting fly control early in the season, using multiple management strategies, managing the use of insecticides with mode of action rotation, and develop a community of producers who are aware of face flies and pinkeye. Face fly abundance on 10% of the animals in a herd should be estimated weekly to identify the most fly-ridden individuals or groups. To understand which control strategies work, producers should record all control efforts and diseases weekly. These records should include recording the approximate fly numbers before, during, and after a fly season, recording any changes in profit margins or animal production, and comparing control-free herds with controlled herds on the same farm. By beginning control efforts in mid-spring, when the first flies begin to start feeding can help to keep the fly population at a low level throughout a grazing season. When beginning face fly management programs, multiple strategies are necessary. This includes adding shelters in pastures to concentrate dung and increase the rate of trampling, herding cattle into screened-in shelters if a pinkeye outbreak occurs to prevent fly immigration and breeding, and quarantining, monitoring, and treating infected animals. Upon discovering pinkeye, producer should immediately begin fly control, antibiotic regimens, quarantine infected cattle, and vaccination of healthy cattle. Use insecticides only in case of disease and fly outbreaks. This generally includes using insecticides only intended for that fly species and life stage, treating the face and surrounding eye regions of cattle with insecticide when used, treating diseased animals with insecticides until they are disease-free, and using multiple modes of action to mitigate development of resistance (see the IRAC or ask your local extension agent). Face flies are strong fliers and can disperse great distances (Sabrosky 1961, Peck et al. 2014); thus, neighboring areas with large face fly populations are usually supplying face flies to areas surrounding them. Therefore, keep in
contact with local cattle farmers. This is not only helpful for synchronizing control efforts but can be useful in forewarning against any disease outbreaks.

Future Strategies and Challenges for Sustainable Management

While face flies remain an important pest of pastured animals and a vector of a number of different pathogens that negatively affect animals, the pace of face fly research has declined dramatically from the 1960s to present. A quick Web of Science search comparing face fly research to other fly species over the past 70 yr highlights the dearth of research on face flies (Fig. 7). This lack of research may be due to a number of factors, including elimination or merging of entomology programs, lack of replacement hires, shift to medical entomology, lack of funding in veterinary entomology, and lack of training opportunities for graduate and professional students (Mullens et al. 2018). We argue that this insect is still important and warrants future research, some strategies and ideas are presented below.

1. Sensors, monitoring, analysis, and reporting technologies (SMART). The current norms of monitoring and managing face flies are as responses to pinkeye or the onset of other pests (e.g., horn flies) or pathogens (e.g., Brucellosis). The current strategies do not emphasize prevention and detection, but instead are responsive to a problem. It is essential that SMART improvements be made to prevent disease onset by improving face fly monitoring and action thresholds that encompass fly populations around the farm and on the animal, as well as responses to animal health, welfare, and economics. As described, SMART technologies are not preventative but a substitute scouting technology leading to a treat/no-treat decision; a response to a problem detected by a SMART device instead of human sampling or observation. SMART technologies can include wearable technologies that detect change in pressures or animal defense responses, visual technology that automates detection of a fly’s morphology, or auditory technology that recognizes a fly’s wing beat frequency or an animal’s distress call. Use of drones around a farm for pest management is coming in agricultural-row-crop entomology; perhaps drones can be used for face fly management as well. Results from the SMART technologies should be incorporated into a dynamic managing platform that helps a producer monitor face fly populations and prevent a problem from occurring. Such a platform can incorporate climatic and economic data to help a producer decide if it is currently economical or sustainable to treat the pest population or if the population is tolerable.

2. Developing sustainable and/or organic face fly management options for producers. Current face fly management strategies are designed to take advantage of their use of fresh dung pats for oviposition. IGRs are fed to cattle and the active ingredient is excreted in dung, resulting in termination of the fly’s immature stage of development. Since beef herds can be quite numerous, adult treatment applications are designed to be efficient and a combination of methods are often used (e.g., pour-ons, back rubbers, dust bags, ear tags). However, face fly insecticide resistance, nontarget effects, and use of chemicals on food animals limit the sustainable and environmentally healthy use of chemical control methods. Thus, it is essential that sustainable methods are developed for limiting the damage and economic losses caused by face flies. There is a need for improved trapping for control of face flies because few traps are designed to target this specific species. Face flies are incidentally collected in traps designed for stable and horn flies. Additionally, there is a need not only to develop new modes of action for face fly control, but more importantly to improve delivery mechanisms of the current management strategies that can help reduce the development rate of insecticide resistance. Biological control options show little practical feasibility at present, yet natural enemies become more important as few products are available that can be used in organic systems.

Fig. 7. Results of a Web of Science search of common name with Latin name of the flies of pastured cattle indicate face flies (A) have had a steady decline of published articles over the past 70yr compared to house flies (B), stable flies (C), and horn flies (D).
Genetic methods for face fly control should be evaluated as well as identifying potential mechanisms for host tolerance and resistance to face flies (and their pathogens). Importantly, all methods of management should include the use of sustainable economic thresholds.

3. Systems approach to managing face fly populations. External factors (e.g., environment, climate, human behavior and perception, host genetics, and consumer preferences) alter face fly populations. Organic dairy herds that have significant face fly problems may be at a greater risk of increased incidence of pinkeye if the pathogen is present. Because few management options exist and are often ineffective, consumer preference for organic dairy milk is likely increasing face fly populations. High face fly populations may result in decreased animal health and welfare and milk production, a simultaneous increase in pathogen incidence, increased fly management efforts by the producer, and negative non-target effects. Additionally, these problems are likely heterogeneous over space and time due to the environment and climate. Thus, there is a current need to assess face fly populations in different systems to identify baseline populations. Having these baseline datasets will allow us to identify positive and negative effects associated with face fly population responses to farm changes, land use changes, and/or changes in producer management practices. As public perception continues to drive economic markets, it is important to understand how producers and consumers perceive face fly populations and what changes each are willing to adopt to reduce populations and manage disease incidence. In the process of managing face flies, it is essential that future research encompass not only effects of management, climate, and perceptions of face flies but also any additional positive or negative effects associated with management practices in different systems.

4. The ongoing need to understand the fundamental biology of face flies. While face flies are not a primary pest in livestock production, their presence contributes to economic losses as well as losses associated with animal health and welfare. It is critical that fundamental research continues to focus on understanding the face fly's biology, ecology, distribution, physiology, genetics, and then learn how each responds to different climates, environments, and management practices. It is essential that the face fly genome is assessed not only effects of management, climate, and perceptions of face flies but also any additional positive or negative effects associated with management practices in different systems.

References Cited

Alexander, D. 2010. Infectious bovine keratoconjunctivitis: a review of cases in clinical practice. Vet. Clin. Food Anim. 26: 487–503.

Angelos, J. A. 2015. Infectious bovine keratoconjunctivitis (pinkeye). Vet. Clin. Food Anim. 31: 61–79.

Angelos, J. A., R. G. Bonifacio, L. M. Ball, and J. F. Hess. 2007. Prevention of naturally occurring infectious bovine keratoconjunctivitis with a recombinant \textit{Moraxella bovis} pilin-\textit{Moraxella bovis} cytotoxin-ISCOM matrix adjuvanted vaccine. Vet. Microbiol. 125: 274–283.

Angelos, J. A., V. M. Lane, L. M. Ball, and J. F. Hess. 2010. Recombinant \textit{Moraxella bovoculi} cytotoxin-ISCOM matrix adjuvanted vaccine to prevent naturally occurring infectious bovine keratoconjunctivitis. Vet. Res. Commun. 34: 229–239.

Angel-Sahagún, C. A., R. Lezama-Gutiérrez, J. Molina-Ochoa, E. Galindo-Velasco, M. López-Edwards, O. Rebollo-Dominguez, C. Cruz-Vázquez, W. P. Reyes-Velázquez, S. R. Skoda, and J. E. Foster. 2005. Susceptibility of biological stages of the horn fly, \textit{Haematobia irritans}, to entomopathogenic fungi (Hypomycetes). J. Insect Sci. 5: 50.

Andres, J. J., R. E. Wright, K. S. Lusby, and R. W. McNew. 1982. Effect of face flies (Diptera: Muscidae) on weight gains and feed efficiency in beef heifers. J. Econ. Entomol. 75: 794–797.

Andres, J. J., R. E. Wright, P. B. Barto, and K. S. Lusby. 1984. Transmission of \textit{Moraxella bovis} from blood agar cultures to Hereford calf by face flies (Diptera: Muscidae). J. Econ. Entomol. 77: 394–398.

Arnason, J. T., S. R. Sims, and I. M. Scott. 2012. Natural products from plants as insecticides. Encycl. Life Support Systems. 1–8.

Axtell, R. C. 1986. Fly control in confined livestock and poultry production. CIBA-GEIGY Corporation, Greensboro, NC.

Barkema, H. W., M. A. G. von Keyserlingk, T. J. G. M. Lam, C. Luby, J.-P. Roy, S. J. LeBlanc, G. P. Keeffe, D. F. Kelton, S. J. I. Le Blanc, et al. 2015. Changes in the dairy industry affecting dairy cattle health and welfare. J. Dairy Sci. 98: 7426–7445.

Barson, G., N. Renn, and A. F. Bywater. 1994. Laboratory evaluation of six species of entomopathogenic fungi for the control of the house fly (\textit{Musca domestica L.}), a pest of intensive animal units. J. Invertebr. Pathol. 64: 107–113.

Bay, D. E., C. W. Pitts, and G. Ward. 1969. Influence of moisture content of bovine feces on oviposition and development of face fly. J. Econ. Entomol. 62: 41–44.

Bech-Nielsen, S., S. Bornstein, D. Christenson, T. B. Wallgren, G. Zakrisson, and J. Chirico. 1982. \textit{Parafilaria bovicola} (Tubangui 1934) in cattle: epizootiology-Vector studies and experimental transmission of \textit{Parafilaria bovica} to cattle. Am. J. Vet. Res. 43: 948–954.

Bech-Nielsen, S., S. Hugoson, and M. Wold-Troell. 1983. Economic evaluation of several control programs for the cattle nematode \textit{Parafilaria bovica} using benefit-cost analysis. Prev. Vet. Med. 1: 303–320.

Benson, O. L., and C. W. Wingo. 1963. Investigations of the face fly in Missouri. J. Econ. Entomol. 56: 251–258.

Berkelbie, D. R., R. D. Hall, and J. J. Webber. 1981. Field association of female face flies with \textit{Moraxella bovis}, and etiological agent of bovine pinkeye. J. Econ. Entomol. 74: 475–477.

Bezanson, G. A., and K. D. Floate. 2019. An updated checklist of the Coleoptera associated with livestock dung on pastures in America north of Mexico. Coleopt. Bull. 73: 655.

Bickle, R. L. 1961. Parasites of the face fly, \textit{Musca autumnalis}, in New Hampshire. J. Econ. Entomol. 54: 802.

Bloomquist, J. R. 1993. Toxicology, mode of action and target site-mediated resistance to insecticides acting on chloride channels. Comp. Biochem. Physiol. C. Comp. Pharmacol. Toxicol. 106: 301–314.

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Kaya, H. K., R. D. Moon, and P. L. Witt. 1979. Influence of the nema-

dode, Heterostylenchus autumnalis, on the behavior of face fly, Musca

autumnalis. Environ. Entomol. 8: 537–540.

Kears, C. W. 1936. The mode of action of insecticides. Ann. Rev. Entomol.

1: 123–148.

Kessler, H., and E. U. Balsbaugh. 1972. Succession of adult Coleoptera in

bovine manure in east central South Dakota. Ann. Entomol. Soc. Am. 65:

1333–1336.

Khater, H. F. 2012. Prospects of botanical biopesticides in insect pest manage-

ment. Pharmacologia. 3: 641–656.

Kienitz, M. J., B. J. Heins, and R. D. Moon. 2018. Evaluation of a commercial

cavacuum fly trap for controlling flies on organic dairy farms. J. Dairy Sci.

101: 4667–4675.

Kim, Y., E. S. Krafus, T. B. Bailey, and S. Zhao. 1995. Mode of inheritance of

face fly diapause and its correlation with other developmental traits. Ecol.

Entomol. 20: 359–366.

Klimaszewski, J. 1984. A revision of the genus Aleochara Gravenhorst of

America North of Mexico (Coleoptera: Staphylinidae, Aleocharinae).

Mem. Entomol. Soc. Canada. 129: 3–211.

Klimaszewski, J., and F. Génier. 1987. A revision of the genus Aleochara

Gravenhorst of America north of Mexico (Coleoptera: Staphylinidae, Aleocharinae).

Supplement 4. New distribution data and description of two new species. The Coleopterists’ Bulletin, 241–248.

Knapp, F. W., R. A. Battles, and K. A. Schwinghammer. 1984. Effects of application date and selective mortality of eggs and larvae of the face fly, Musca autumnalis. Annu. Rev. Entomol. 39: 318–324.

Krafsur, E. S. 1999. Age structure of overwintered face fly populations estimated by pteridine concentrations and ovarian dynamics. Med. Vet. Entomol. 13: 41–47.

Krafsur, E. S., R. D. Moon, and K. L. Ruse. 1999. Dynamics of diapause recruitment in populations of the face fly, Musca autumnalis. J. Agric. Entomol. 1: 123–136.

Krafsur, E. S., and W. C. I. Black. 1982. Congenitally induced mortality in face flies (Diptera: Muscidae) following adult exposure to diflubenzuron-treated surfaces. J. Med. Entomol. 19: 191–194.

Krafsur, E. S., and C. J. Church. 1983. Mortality of eggs and larvae of the face fly (Diptera: Muscidae) after exposure of adults to surface treated with BAY SIR 8514 and penfluron. J. Econ. Entomol. 76: 1350–1352.

Krafsur, E. S., and F. H. Herd. 1984. Effects of application date and selective tagging of cows and calves with fenvalerate ear tags for the control of the horn fly and face fly. J. Agric. Entomol. 1: 58–63.

Krafsur, E. S., F. H. Herd, and K. A. Schwinghammer. 1983. Comparative toxicity of selected insecticides to laboratory-reared and field-collected face flies (Diptera: Muscidae). J. Econ. Entomol. 78: 860–862.

Krafsur, E. S., C. J. Church, and C. M. Ernst. 1981. Juvenile hormone mimics as feed additives for control of the face fly, Musca domestica. J. Econ. Entomol. 74: 295–296.

Krafsur, E. S., and R. D. Moon. 1997. Bioinomics of the face fly, Musca autumnalis. Annu. Rev. Entomol. 42: 503–523.

Krafsur, E. S., and W. C. I. Black. 1992. Analysis of isozyme loci in the face fly, Musca autumnalis De Geer. Biochem. Genet. 30: 625–634.

Krafsur, E. S., C. J. Church, K. M. Elvin, and C. M. Ernst. 1983. Epizoosytology of Heterotylenchus autumnalis (Nematoda) among face flies (Diptera: Muscidae) in central Iowa, USA. J. Med. Entomol. 20: 318–324.

Krafsur, E. S., A. L. Rosales, and Y. Kim. 1999. Age structure of overwintered face fly populations estimated by pteridine concentrations and ovarian dynamics. Med. Vet. Entomol. 13: 41–47.

Krafsur, E. S., R. D. Moon, Y. Kim, and A. L. Rosales. 1999. Dynamics of dia-

pause recruitment in populations of the face fly, Musca autumnalis. Med. Vet. Entomol. 13: 337–348.

Labib, I. M., and M. Rady. 2001. Application of Bacillus thuringiensis in poultry houses as a biological control agent against the housfly, Musca domestica sordoros. J. Egypt. Soc. Parasitol. 31: 531–544.

Legner, E. F. 1978. Natural enemies imported in California for the biological control of face fly, Musca autumnalis De Geer, and horn fly, Haematobia irritans (L.), pp. 77–79. In Proceedings and papers of the Forty-sixth Annual Conference of the California Mosquito and Vector Control Association, Inc., January 29-February 1, 1978, held at the Ahwahnee Hotel, Yosemite, California. CMVCA Press.
Sinclair, J. A., B. S. Cooper, and I. J. Steffert. 1986. A survey of infectious bovine keratoconjunctivitis in the Gisborne and Hunterville regions of New Zealand. N. Z. Vet. J. 34: 121–125.

Skoda, S. R., J. B. Campbell, and S. E. Kunz. 1987. Wide-area treatment of cattle for horn flies and face flies (Diptera: Muscidae) in south-central Nebraska. J. Econ. Entomol. 80: 811–816.

Slatter, D. H., M. E. Edwards, C. D. Hawkins, and G. E. Wilcox. 1982a. A national survey of the clinical features, treatment and importance of infectious bovine keratoconjunctivitis. Aust. Vet. J. 59: 69–72.

Slatter, D. H., M. E. Edwards, C. D. Hawkins, and G. E. Wilcox. 1982b. A national survey of the occurrence of infectious bovine keratoconjunctivitis. Aust. Vet. J. 59: 65–68.

Snowder, G. D., L. D. Van Vleck, L. V. Cundiff, and G. L. Bennett. 2005. Genetic and environmental factors associated with incidence of infectious bovine keratoconjunctivitis in preweaned beef calves. J. Anim. Sci. 83: 507–518.

Sommer, C., B. Steffansen, B. Overgaard Nielsen, J. Gronvold, K.-M. Vagn Jensen, J. Brochner Jespersen, J. Springborg, and P. Nansen. 2018. On the behavior and ecology of the face fly, Musca autumnalis De Geer. J. Insect Physiol. 15: 1199–1214.

Valder, S. M., T. L. Hopkins, and S. A. Valder. 1969. Diapause induction and changes in lipid composition in diapausing and reproducing facelies, Musca autumnalis. J. Insect Physiol. 15: 601–603.

Vockeroth, J. R. 1953. Musca autumnalis Deg. in North America (Diptera: Muscidae). Can. Entomol. 85: 422–423.

Watson, D. W., C. J. Geden, S. J. Long, and D. A. Rutz. 1995. Efficacy of Beauveria bassiana for controlling the house fly and stable fly (Diptera: Muscidae). Biol. Control. 5: 405–411.

Webber, J. J., and L. A. Selby. 1981. Risk factors related to the prevalence of infectious bovine keratoconjunctivitis. J. Am. Vet. Med. Assoc. 179: 823–826.

Weeks, E. N., E. T. Machtinger, S. A. Gezan, P. E. Kaufman, and C. J. Geden. 2017. Effects of four commercial fungal formulations on mortality and sporulation in house flies (Musca domestica) and stable flies (Stomoxys calcitrans). Med. Vet. Entomol. 31: 15–22.

Whistlecraft, J. W., C. R. Harris, J. H. Tolman, and A. D. Tomlin. 1985. Mass-rearing technique for Aleochara bilineata (Coleoptera: Staphylidinae). J. Econ. Entomol. 78: 995–997.

Williams, R. E. 2009. Importance of arthropods, pp. 1–10. In R. E. Williams (ed.), Vet. Entomol. Livest. Companion Anim. CRC Press, Boca Ratun, Florida.

Williams, R. E., and E. J. Westby. 1980. Evaluation of pyrethrins impregnated in cattle ear tags for control of face flies and horn flies. J. Econ. Entomol. 73: 791–792.

Wingo, C. W., G. D. Thomas, G. N. Clark, C. E. Morgan, G. N. Clarke, and C. E. Morgan. 1974. Succession and abundance of insects in pasture manure: relationship to face fly survival. Ann. Entomol. Soc. Am. 67: 386–390.

Woolley, C. E., S. Lachance, T. J. Devries, and R. Bergeron. 2018. Behavioural and physiological responses to pest flies in pastured dairy cows treated with a natural repellent. Appl. Anim. Behav. Sci. 207: 1–7.

Wylie, H. G. 1973. Parasites of face fly, Musca autumnalis (Diptera: Muscidae), and associated Diptera near Belleville, Ontario. Can. Ent. 105: 257–261.

Yang, T., G. Stoopeen, G. Wiegens, J. Mao, C. Wang, M. Dicke, and M. A. Jongma. 2012. Pyrethrins protect pyrethrum leaves against attack by western flower thrips, Frankliniella occidentalis. J. Chem. Ecol. 38: 370–377.