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Profile

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 prestomal 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 pats, 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 propleuron, 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 (*Pollenia 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 (F_0–F_1) can take as many as 62 d at 15°C, and as

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Fig. 1. Face fly females (6–10 mm) have a dull gray thorax with four thoracic stripes (Williams 2009) and sponging mouthparts used to ingest fluids. The female (left) has a wider vertex between compound eyes, and darkly checkered abdomen that is gray-black, except for the first abdominal tergite which has yellow patches at its lateroventral margins. The male (right) has a shiny black thorax, a narrower vertex, and a bright golden abdomen starting at the second segment with one black stripe down the middle. Both sexes have a sharply curved M1 wing vein (arrows), characteristic of *Musca* spp., and distinctive tufts of setae on alary sclerites ventral to wing bases and tiny setae ('hairs') between the 1st thoracic spiracle and the head (Loomis et al. 1971). Photo credit: Matt Bertone.

Fig. 2. Face fly eggs (left) with distinctive brown respiratory stalks are inserted stalk up in dung pat surface. First instars (right) hatch and burrow deeper into the dung. Photo credit: Matt Bertone.

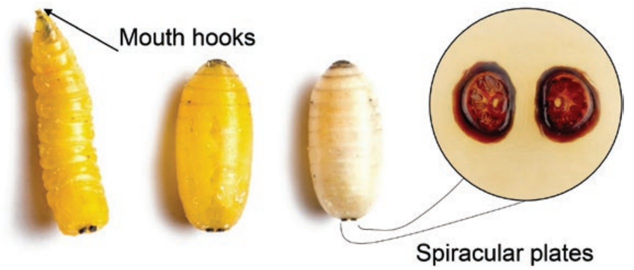

Fig. 3. Left to right, bright yellow third instar (6–10 mm), yellow prepupa, and white calcified puparium with pupa inside. Larvae have pointed mouth hooks on head end. Posterior ends have back-to-back D-shaped spiraclular plates with sinuous peritremes visible throughout larval-pupal metmorphosis. Photo credit: Matt Bertone.

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 et 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

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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

Fig. 4. Face flies feeding on the eyes and facial secretions of a horse, cow, and calf. Horse photo by Kelly Loftin, cattle photos by H. J. Meyer.

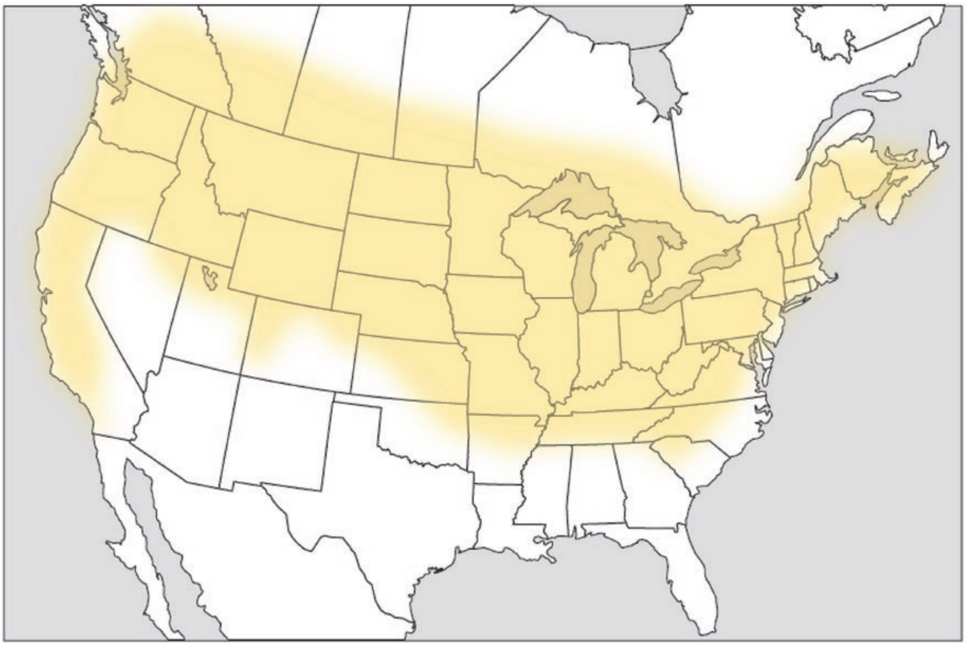

Fig. 5. Current distribution of face fly in the United States and Canada. Adapted from Krafsur and Moon (1997).

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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[a]	Brucellosis	*Brucella abortus* (Schmidt) Meyer & Shaw	Profuse sweating, fever, joint/muscle pain	Cattle Fetuses		Abortion, Arthritis
Eyeworms[b]	Bovine and Equine Thelaziasis	*Thelazia gulosa* Railliet & Henry *T. skrjabini* Erschow, *T. lacrymalis* Gurlt	'Worms' infesting tear ducts and eyes, IBK-like symptoms	Cattle and Horses	North America	IBK
Green-muscle Disease[a]	Hemorrhagic Bovine Filariasis	*Parafilaria bovicola* Tubangui	Dermal and subcutaneous lesions ('bleeding points')	Cattle	South Africa, Sweden, France, northern Africa, Rumania, India, the Philippines	Death
IBR[c]	Infectious Bovine Rhinotracheitis	Virus	IBK-like symptoms	Calves; yearling cattle		IBK
Mastitis[c]	Mastitis	*Trueperella* (formerly *Corynebacterium*) pyogenes (Glage)	Inflamed utter tissue (swelling, redness, hardness, pain)	Lactating Cattle		Pain; clotted, flaky, or watery milk; loss of teats
Pinkeye or IBK[b,d,e]	Infectious Bovine Keratoconjunctivitis	*Moraxella bovis M. bovoculi Mycoplasma* spp.	Photophobia, corneal ulceration, opacity, and lacrimation	Calves; yearling cattle	World-wide	Temporary-permanent blindness; scarring
Allergens[f]				Humans		

Species author(s) and lettered journal references are listed in superscript above the species or common name.
[a]Krafsur and Moon (1997).
[b]Pickens and Miller (1980).
[c]Hall (1984).
[d]Brown et al. (1998).
[e]O'Connor et al. (2012).
[f]Moon (2019).

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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 prestomal 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 irritants, 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 prestomal 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 crossbreeds (Snowder et al. 2005). 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. 1982a). 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

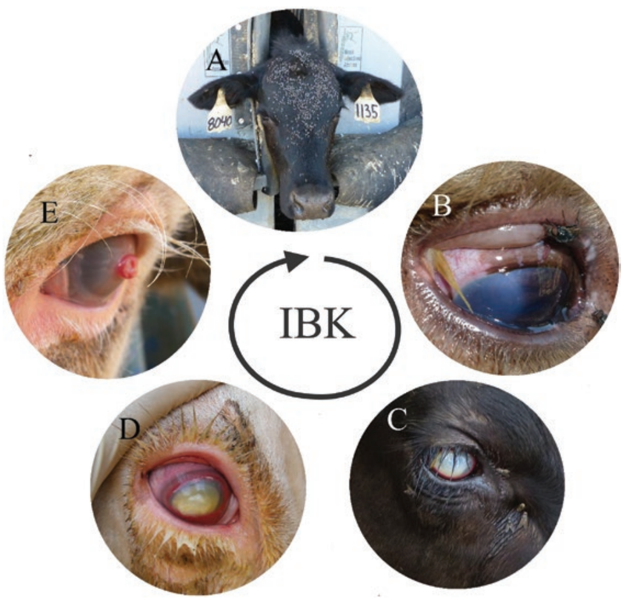

Fig. 6. Progression of infectious bovine keratoconjunctivitis (IBK) or bovine pinkeye disease. (A) Face flies feeding on face of cow. (B) Stage I IBK infection presents with slight corneal opaqueness. Note the inner eyelid (conjunctiva) is not red or inflamed. (C) Stage II IBK infection presents with an opaque eye with surrounding tissues inflamed and excessive tear production. Note face flies feeding on tears. (D) Stage III IBK infection presents the eye with a corneal perforation where a bulging or elongated eye structure forms that leads to eventual rupture and permanent scarring. (E) Stage IV IBK infection clinical sign includes corneal ulceration, where a raised lesion disrupts the eye shape and membrane. Photos by John Angelos.

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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. 2005). 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 with 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 are found on nearly every continent. Non-biting flies serve as intermediate hosts and vectors. Face flies transmit *T. gulosa* Railliet and Henry, *T. lacrymalis* (Gurlt), and *T. skrjabini* 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 *Thelazi* development in face flies is also available elsewhere (Geden and Stoffolano 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: Filariidae) (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 naïve 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 twitches, 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

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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, oiler/rubs, 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 Matthysee 1967). More recently, photography has been used to document numbers of face flies, and horn flies, too. Animal behaviors can also be used to gauge animal comfort. For example, heifers not treated for face fly control had significantly more bunching episodes and spent more time bunched per day compared with treated herds (Schmidtmann and Valla 1982). The number of episodes and time bunched was also positively correlated with increasing face fly pressure, and bunching was indicative of 9–12 flies per face (Schmidtmann and Valla 1982). Behavioral responses were also reported where face flies (or house flies as the authors did not differentiate) were positively and significantly associated with partial tail flicks and leg stamps in Holstein dairy cows (Woolley et al. 2018). Monitoring fly numbers, animal discomfort, disease presence, financial records, and fly control costs should be key to improving a farm's fly management program.

Traps to Remove Flies From Animal Environment

Sticky traps of different designs were used to measure abundance of face flies for research purposes (Pickens and DeMilo 1977, Kaya and Moon 1978, Peterson and Meyer 1978, Johnson and Campbell 1987). Traps consisted of glossy-white plywood pyramids coated with an adhesive. These captured more face flies than alternative shapes and colors (Pickens et al. 1977). Numbers captured were greatest on traps closest to cattle, but traps needed to be placed outside of fencing to prevent damage by cattle; however, current technology might allow traps to be placed closer to cattle.

Based on presumption that flies disperse among neighboring farms, white tetrahedral sticky traps were evaluated alone and in combination with tetrachlorvinphos (a feed-thru organophosphate insecticide) in a 4-yr area-wide control program in Maryland (Miller et al. 1984). Face fly control with pyramids alone was insufficient, even with as many as one trap for every three cattle. A further practical limitation of sticky traps for face fly control is that pastures and rangeland, where face flies occur, can be relatively inaccessible, which makes maintenance to replenish sticky trap surfaces prohibitively expensive. Traps placed at water tanks and salt or grain feeding stations may be more practical, especially for herds managed with rotational grazing. It remains to be seen if placement there could provide a satisfactory level of control.

Walk-thru and vacuum traps provide another alternative to insecticides. An early design for horn fly control required cattle to walk through a darkened, building-like structure where brushes disturbed flies from passing animals. Disturbed flies would then move to lighted trap sides where they were passively captured (Bruce 1938). Bruce traps were successful in reducing numbers of horn flies, but were less 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 watery, larvae will suffocate 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 Hermanussen 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).

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Table 2. Insecticides and modes of action proposed for adult and larval face fly control, in historical order of appearance in the literature[a]

Chemical (IRAC Group No.[b])	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, oilers/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[c] (uncertain)	Neurotoxic, neuromodulator octopamin, GABA-gated chloride channels	Adult	Sprays	Isman (2006), Cloyd et al. (2009); Khater (2012)
Tolfenpyrad[d] (21A)	Mitochondrial complex I electron transport inhibitor (METI)	Adult	Ear Tag	Commercial launch

[a]See Nausen et al. (2019) and access www.veterinaryentomology.org for a list of labeled fly control products.
[b]www.irac-online.org.
[c]Minimum risk pesticides exempt from Environmental Protection Agency registration under Section 25b of the Federal Insecticide Fungicide Rodenticide Act.
[d]The different compounds in this mode of action group (21A) belong to several different chemical classes. Tolfenpyrad is a pyrazole insecticide.

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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 dug 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, Anthomyidae, 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 endoparasites; *Aphaereta pallipes* (Say) is a gregarious species and *Alysia* 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* Latreille 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 cyclorraphous 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. bulineata* (Gyllenhal) on *Delia antique* (Meigen) (Whistlecraft 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 hypertrophy virus could infect face flies as well as stable flies (*Stomoxys calcitrans* L.), black dump flies (*Hydrotaea aenescens* 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, Labib 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. *Paraiotonchium 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, Krafsur 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 *P. autumnale* 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 feed-through products are used to manage face flies. Various modes of

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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; Hogsette 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 pyrethoids (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 diflubenzuron, 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-aminobutryic 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 (Fukuto 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 Bipontinus, are ground into powder and extracted using solvents (Casida and Quistad 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 Hansens 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 repellency, 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 (Khater 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

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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 effected 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 Berkebile 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* Linnaeus) are more resistant to pinkeye infection than temperate breeds (*Bos taurus* Linnaeus) (Slatter et al. 1982b, Snowder et al. 2005). Light-skinned animals, such 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, Snowder 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 1978, 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 regiments, 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

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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 filth flies 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.

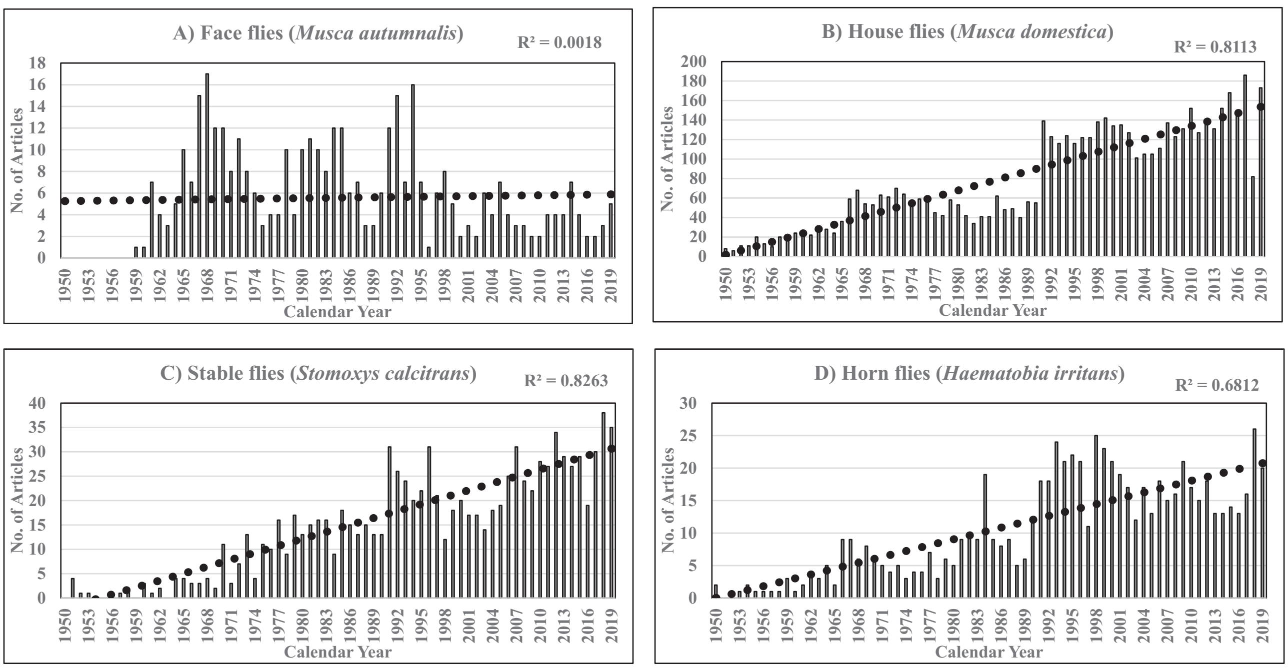

Fig. 7. Results of a Web of Science search of common name with Latin name of the flies of pastured cattle indicate face flies (A) have had a steady decline of published articles over the past 70 yr compared to house flies (B), stable flies (C), and horn flies (D).

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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 flies 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 completed and annotated which will allow for further research into comparative genomics (e.g., useful for identifying mechanisms for resistance), population genetics/genomics (e.g., useful for understanding dispersal), and to design and evaluate novel management approaches (e.g., lethal-gene drive). The combination of physiology and genomic studies can lead to understanding the epigenetics of the face fly and how populations respond to nature. Habitat and distribution studies which involve the immature development sites (e.g., microbial community studies) and pasture habitats (e.g., ecological and/or remote sensing studies) can help describe the ecological niche of face flies.

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