Journal of Integrated Pest Management, (2022) 13(1): 14; 1–18
https://doi.org/10.1093/jipm/pmac010
Profile

A Call for the Development of a Sustainable Pest Management Program for the Economically Important Pest Flies of Livestock: a Beef Cattle Perspective

K. V. Smith,[1,2] K. L. DeLong,[1] C. N. Boyer,[1] J. M. Thompson,[1] S. M. Lenhart,[3] W. C. Strickland,[3,4] E. R. Burgess, IV,[5] Y. Tian,[5] J. Talley,[6] E. T. Machtinger,[7] and R. T. Trout Fryxell[2,8]

[1]Department of Agricultural and Resource Economics, University of Tennessee, Knoxville, TN, USA, [2]Department of Entomology and Plant Pathology, University of Tennessee, Knoxville, TN, USA, [3]Department of Mathematics, University of Tennessee, Knoxville, TN, USA, [4]Department of Ecology and Evolutionary Biology, University of Tennessee, Knoxville, TN, USA, [5]Department of Entomology and Nematology, University of Florida, Gainesville, FL, USA, [6]Department of Entomology and Plant Pathology, Oklahoma State University, Stillwater, OK, USA, [7]Department of Entomology, Pennsylvania State University, University Park, PA, USA, and [8]Corresponding author, e-mail: rfryxell@utk.edu

Subject Editor: Eric Hoffman

Received 24 January 2022; Editorial decision 23 March 2022

Abstract

Filth fly pests have a substantial impact on livestock production; annual losses from filth flies were estimated at over US$1.5 billion in 1981. Knowing filth fly management and animal production have changed significantly over the past 40 yr, our objective is to lay the foundation for the development of a transdisciplinary integrated pest management (IPM) approach that considers the economics of controlling flies in animal production, with most of the examples provided towards beef cattle production systems. By performing an in-depth literature review, it is our goal to highlight losses and expenditures associated with the damages caused by these flies, discuss current management strategies for the system, and propose industry needs in terms of research gaps and producer education to enhance sustainable livestock production. Immediate industry needs include: (1) developing dynamic economic thresholds incorporating animal welfare, economics, impacts of chemical use, and climate-related responses; (2) improving monitoring methods to improve surveillance efforts for flies as a system and how all types collectively shape the system; and (3) updating economic loss assessments to account for losses due to animal defensive behaviors, reduced feed efficiency, and unplanned expenditures. While we focus on the beef cattle system in the United States, this paper is meant to provide an argument for research in worldwide livestock production (e.g., dairy, poultry, swine, and small ruminant).

Key words: filth fly, livestock pest, cattle, IPM, sustainable

Economic entomology is a multi-disciplinary field that assesses pest populations and management strategies, while ensuring the economic feasibility of crop production. To implement new practices on their operations, farmers in crop production and producers in livestock production must be able to measure the financial and non-financial costs and benefits of doing so; thus, entomologists should perform economic evaluations in line with producer plans and/or objectives (Onstad and Knolhoff 2009). For many, economic entomology is the study of crop yields and losses, and this is also the case for animal production and costs associated with livestock pests. To understand the economic impact of livestock pests (specifically filth flies), it is important to define 'loss' and 'expenditure,' which are often incorrectly used interchangeably (McInerney et al. 1992). The term 'loss' is a loss of production (e.g., reduced weight gain, lower milk production, loss of product value from consumer reaction to perceived animal welfare or food safety); whereas, the term 'expenditure' refers to costs associated with prevention and control (e.g., ear tag, insecticide spray) (Morris 1997, Rushton 2009). A pest's total economic impact is the sum of losses and expenditures. When studying the economic impacts specifically of livestock pests in animal agriculture, attention should be paid to (1) reduced animal production; (2) reduced quality of animal products; (3) additional costs needed to recover the desired level of animal production (e.g., increase in feed, pest management costs, treatment, sanitation, etc.); (4) costs of human health related to zoonoses and disease control; (5) impact on animal welfare; and (6) restrictions on domestic and international trade of animals or animal products. Nuisance and other peripheral effects resulting from filth

© The Author(s) 2022. Published by Oxford University Press on behalf of Entomological Society of America.
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

fly activity also have an additional economic impact (Skoda and Thomas 1993). Controlling production costs is important for all animal commodities such that a perceived minor loss in production efficiency can lead to a notable reduction in profit when multiplied over all animals within an operation/facility. In addition, fly pests and their associated pathogens can create food safety concerns (e.g., transmission of *Escherichia coli* or *Salmonella* species) for the consumer that reduce product demand and value (reviewed in Nayduch and Burris 2017, Tomberlin et al. 2017).

Most entomologists are familiar with pest populations reaching economic injury levels (EILs) when the pest population occurs at a density that will cause measurable economic damage to the crop/livestock animal of interest (Stern et al. 1959, Headley 1972). These values are determined based on the economic value of the crop/livestock loss, which equals the cost of controlling the pest to prevent those losses (Norris et al. 2003). To help producers decide when to implement pest control measures, experts have determined economic thresholds (ETs) for common pests of agricultural crops and livestock. Economic thresholds are lower values than EILs and are the density of pests required before control measures should be initiated to prevent pest densities from exceeding the EIL (Stern et al. 1959). For some, using a statistical threshold (ST) identifies a pest population that is statistically more abundant than should be expected (either from a previous time point or an average time point), but is often not associated with economic impacts.

Filth fly pests have a substantial impact on livestock production. Damage caused by these flies is commonly evaluated in terms of direct and indirect damage as well as peripheral effects (Williams 2009, Machtinger et al. 2021). In animal agriculture, direct damage occurs due to contact between the pest and its host, resulting in direct injury to the host in the form of skin/tissue damage and/or physiological responses such as reduced fertility, growth, and lactation (Williams 2009, Machtinger et al. 2021). Animal disturbance (e.g., alteration of normal behaviors and self-inflicted wounds resulting from pest avoidance and invasion), transmission of pathogens, and reduced animal welfare are considered indirect damage, which is often difficult to quantify (Williams 2009, Machtinger et al. 2021). Peripheral effects are also difficult to quantify, as these effects include filth fly nuisance, off-target impacts of pesticide application for fly control, and livestock transport bans and/or regulations (Williams 2009, Machtinger et al. 2021). All of these types of damages have associated losses and expenditures.

Producers who use integrated pest management (IPM) attempt to control pests with a combination of tactics producing the best outcomes in terms of economic, ecological, and sociological consequences (Rabb 1972). Multidisciplinary approaches are critical in IPM and include control methods such as cultural strategies, pest resistant or pest tolerant hosts, mechanical and/or physical controls, biological controls, genetic strategies, and chemical tactics (Norris et al. 2003). Two crucial components of a successful IPM plan include monitoring (ongoing or routine assessment efforts) pest populations for surveillance efforts (active and intensive system designed for action) (Christensen 2001). Use of monitoring confirms the identification of the pest and/or problem at specific time points and locations providing a snapshot of the system; meanwhile, use of surveillance facilitates data-driven decisions regarding pest control including if there is a need and if the control method is effective using real-time data. These components can be a direct assessment of the pest or an indirect assessment of the pest's damage to the host. Use of monitoring and surveillance data across a landscape can lead to precision agriculture management, using a combination of temporal, spatial, and individual data to promote sustainability across a landscape, region, and/or community (International Society of Precision Agriculture 2021).

There is a long-term and continually growing need to refine IPM to increase producers' profitability by helping producers make data-driven and sustainable decisions for pest management. This has become critical as pest populations are regulated by the environment (e.g., population response to weather shifts for warmer and wetter days) and the presence of (abundant) pest populations can also change the environment (e.g., use of insecticides vs natural enemies). With rapidly increasing emphasis on sustainability in agriculture, it is imperative that we adapt pest management practices in livestock production to be both environmentally sustainable and economically beneficial. Sustainable methods could include the development of vaccines to target flies and selective breeding of animals (e.g., genetic selection) to reduce losses (Steelman et al. 1991, 1996, 2003; Brown et al. 1992; Pruett et al. 2003; Untalan et al. 2006; Cupp et al. 2010; Domingues et al. 2021). Innovations like these will be key in developing IPM approaches that lower costs and increase effectiveness (Oyzrzún et al. 2008).

The purpose of this manuscript is to evaluate the economic impact and management of three filth fly species that affect livestock, specifically beef cattle; thus, we present the foundation for developing a transdisciplinary IPM approach that considers the economics of controlling flies in animal production. By performing an in-depth literature review, it is our goal to highlight losses and expenditures associated with the damages caused by these flies, discuss current management strategies for the system, and propose industry needs in terms of research and mathematical modeling gaps and producer education to enhance sustainable beef production.

Important Fly Pests of Beef Cattle

One of the challenges to establishing sustainable pest management models is the compartmentalization of the industries. Using the beef industry as an example, each sector presents unique environmental and ecological stresses that can either promote or limit pest populations. Considering the division, it is important to note which sectors are pasture based, including cow-calf operators and stocker operators, and which sectors are primarily outdoor confined (Gerry 2018). These two systems are completely different ecologically, in management strategies employed, and in primary food resources for the animals. Knowing the primary attribute of a fly population is their ecological niche, the habitat helps to determine pest potential. Talley and Machtinger (2020) broadly defined the divisions of the beef industry into extensive and intensive systems. This classification allows pest managers to relate fly populations to both ecologically defined areas of each segment as well as management strategies. Extensive systems are broadly defined as cow-calf or stocker operations with fewer animals per unit of land (Talley and Machtinger 2020) that allow for the proliferation of horn flies (*Haematobia irritans* L., Diptera: Muscidae), face flies (*Musca autumnalis* De Geer, Diptera: Muscidae), and stable flies (*Stomoxys calcitrans* L., Diptera: Muscidae). Intensive systems have a higher animal density (Talley and Machtinger 2020) with stable flies and house flies (*Musca domestica* L., Diptera: Muscidae) being consistent pests. Many production costs are necessary as producers have an average herd size of 43.5 cattle (U.S. Department of Agriculture, National Agricultural Statistics Service 2017) and average veterinary and medicine costs for cow-calf production of US$26 per animal in 2020 (U.S. Department of Agriculture, Economic Research Service 2020). Commodity costs and return data show cow-calf producers' profit margins are small, if positive; thus, minimizing the losses and

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

expenditures associated with pests is important (U.S. Department of Agriculture, Economic Research Service 2020).

Currently, economic impacts of biting flies on cattle production are associated with losses in production and are evaluated by measuring performance and efficiency parameters such as weight gain, weaning weights, and feeding efficiency in the form of gain to feed ratios (Machtinger et al. 2021). Biting flies also cause behavior-related economic impacts when cattle exhibit avoidance behaviors caused by fly feeding. Determining economic impacts of non-biting flies is an additional challenge. These pests cause losses through reduced animal production or performance and require expenditures for treatment. The complexities of the fly species and their inter- and intraspecific interactions further complicate the assessment of economic costs. The impact of flies on animal production is influenced by the presence of multiple animal host species and breeds and the effects of different fly species on hosts, including the effect of animal feeding and management regimes on economic impact. Most importantly, ETs are dynamic and change temporally and contextually (Axtell 1981); for example, expenditures for fly prevention and control are not consistent among producers. The use of insecticides is region-, producer-, and situation-dependent and may not represent the use on an industry-wide level. Management of fly pests includes labor, equipment, fuel, and other costs that are highly specific to the producer and to the facility. Indirect impacts of abundant resident adult fly populations on animal facilities, aesthetic value to potential customers, or social perceptions of animal welfare are difficult to quantify as are other values, such as the storage of manure and increased animal comfort.

The three primary filth flies affecting beef production that have had EILs and ETs determined include horn flies, face flies, and stable flies, which cause a combination of negative effects to animals. Horn fly populations cause significant damage because these ectoparasites blood feed on their hosts 20-40 times per day, causing a variety of damage to beef cattle (Arther 1991, Brewer et al. 2021). Economic thresholds for horn flies range from 10 to 230 flies per animal side, depending on geographical location, environmental factors, and value of the animals (Gordon et al. 1984, Arther 1991, Moon 2019). The losses and expenses associated with face fly populations are often difficult to quantify, but most producers associate losses from infectious bovine keratoconjunctivitis (IBK or pinkeye) with face flies (Sinclair et al. 1986). Because values for measurable damage were insufficient, Krafsur and Moon (1997) could only estimate that the ET for face flies is well above 15 flies per animal; however, the prevalence of pinkeye within a herd often warrants continual face fly control. Stables flies are an endemic pest because these flies develop in the organic hay material and then blood feed on both pastured and confined livestock (Rochon et al. 2021). Taylor et al. (2012) developed an economic model that estimated the economic losses due to stable flies for dairy, cow-calf, stocker, and feeder operations. At the time, there were not enough data to quantify reproductive losses from stable flies (Taylor et al. 2012), but possible additional effects include reduced heifer weight gain, leading to delayed puberty and failure to calve as a two-year-old (Engelken 2008, Taylor et al. 2012). Catangui et al. (1997) determined that the EIL for stable flies in feeder heifers is seven stable flies per foreleg per head per minute, while the ET is estimated to be 15 flies per animal (Berry et al. 1983, Campbell and Berry 1989). A comprehensive review for each fly pest was provided in Brewer et al. (2021), Trout Fryxell et al. (2021), and Rochon et al. (2021).

Without the ability to identify and assess flies and the wide range of ETs, it is difficult for producers to determine when to implement control measures. Moreover, producer and farm demographics, producer perceptions, management strategies, and horn fly seasonality (Smith et al. 2022) influence horn fly management costs. If this occurs for horn flies at cow-calf operations, it is reasonable to assume that these decisions also vary for the other filth flies of concern at different animal agriculture operations.

Current Economic Loss Assessments

Drummond et al. (1981) estimated annual losses from horn flies, stable flies, and face flies to be US$730.3 million, US$398.9 million, and US$53.2 million, respectively. Values adjusted for inflation can be viewed in Table 1. Each estimate was based on weight loss and reduction in milk flow in addition to specific annual losses. Annual losses from horn flies included weight loss per calf, stocker cattle, slaughter cattle (%), and percent reduction in milk flow during the six-month peak summer horn fly season. Annual losses from stable flies included dollars per head weight loss in feedlot cattle and percent reduction in milk flow for the six-month stable fly season. Annual losses from face flies included weight losses in calves. For example, effective fly control in stocker cattle was estimated to have just over an 8% impact on animal performance in the form of average daily weight gains (Lawrence and Ibarburu 2007). With the changes in cattle production practices and management, plus variability in climate, these costs have likely changed over time and updates are an important area of future research. Updating these estimates is warranted, as changes in the management of cattle production, including production practices and consumer perceptions/choice, and changes in response to variability in climate and environment have occurred in the 40 yr since the estimates published by Drummond et al. (1981).

Scientists have begun to further examine the cause of economic losses related to flies associated with animal responses to fly predation. Animal defensive behaviors reduce grazing time, which decreases energy intake while increasing energy output (Todd 1964, Dougherty et al. 1993c); however, these studies have not measured economic losses associated with those behaviors. Okumura (1977) documented a positive correlation between abundance of flies and frequency of tail swishing. Schmidtmann and Valla (1982) found that Holstein herds exposed to ambient face fly activity had a greater

Table 1. Annual economic loss estimates (USD) adjusted for inflation using United States Bureau of Labor Statistics (2021)

Fly Species	Original Estimate	Adjusted Estimate	Source
Horn Fly	$730 million	$2,196 million	Drummond et al. 1981
	$876 million	$1,702 million	Kunz et al. 1991
Face Fly	$52 million	$157 million	Drummond et al. 1981
	$50 million	$97 million	Kunz et al. 1991
Stable Fly	$399 million	$1,199 million	Drummond et al. 1981
	$432 million	$840 million	Kunz et al. 1991
	$2,000 million	$2,310 million	Taylor et al. 2012

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

number and duration of bunching episodes and found a positive correlation between pest intensity and bunching episodes, although no difference in grazing time was observed. Wieman et al. (1992) studied feeder cattle exposed to stable flies and found that bunching and heat stress (indirect effects) were responsible for 71.5% of the cattle's reduced weight gain, while the remaining 28.5% was attributed to fly bites and the energy lost by cattle defensive behaviors against the stable flies (direct effects). Dougherty et al. (1993b) analyzed the effects of face flies on grazing cattle behavior and found that cattle fed deeper in the tall pasture grass in an attempt to dislodge flies resulting in larger bites of grass and therefore more grass intake. Dougherty et al. (1993a) evaluated the behavior of grazing beef cattle when exposed to a release of stable flies every 15 min for one hour of grazing meals and results showed that as more flies were released, cattle's movement rates increased for heads, ears, tails, front and hind legs, and skin twitches. The flies also decreased the time cattle spent at grazing stations; the number of forage bites and dry matter intake also decreased. Subsequent studies concluded that cattle display accelerated herbage intake (attributed to annoyance) and reduced grazing times when stable flies are present (Dougherty et al. 1994, 1995). Mullens et al. (2006) monitored dairy cattle responses to stable flies and suggested that behaviors such as stamping, head throwing, skin twitching, and tail flicking were dependent on the number of flies present on the animals. Thus, it is essential that we improve our understanding of how flies affect individual animals, breeds, and herds in different locations.

Considering the importance of insecticides to the beef industry, a meta-analysis of over 170 different research trials that evaluated the use of pharmaceutical technologies (e.g., insecticides, acaricides, anthelmintics) in beef systems demonstrated that fly control helped producers achieve or exceed breakeven points or the points at which total cost is equal to total revenue (Lawrence and Ibarburu 2007). In the cow-calf sector alone, implementing fly control efforts resulted in 2.56% higher weaning weights, which represents a 3.05% change in breakeven prices if fly control pharmaceuticals were eliminated from the market (Lawrence and Ibarburu 2007). This change in breakeven price represents a US$14.51 cost-per-calf sold if insecticides were eliminated from the beef market. Unfortunately, due to many factors including limited options, fly control is often stopped due to insecticide resistance, regulatory practices, and/or consumer opinions (e.g., producer not recognizing value of fly control, devaluing potential profits), and when this occurs a producer is less likely to reach breakeven points. Additionally, anthelmintics (or dewormers) also influence filth fly populations because stocker operators use these products as an additional fly control technology (Lysyk and Colwell 1996). The combined use of dewormers with insecticides for nematode control and fly control in beef production would result in a loss of ~US$27 per head if both of these were eliminated or deemed ineffective (Lawrence and Ibarburu 2007). When looking at the potential of losing certain pharmaceutical technologies across all segments of the beef industry, it should be noted that dewormers were considered a very important technology (Lawrence and Ibarburu 2007). In all beef sectors most fly control applications are in the form of dewormers that are applied as pour-ons. If this method is lost across all segments of the beef industry, it would increase the breakeven price by 19%, which would represent a cost of $190/ head produced in modern beef production (Lawrence and Ibarburu 2007). It is vital to understand how to incorporate current fly control techniques into both economic and environmental models for the sustainability of fly control measures within the beef industry.

Animal Welfare

Animal welfare is another aspect to consider in terms of filth fly damages to cattle and is an area of growing importance to consumers. The World Organization for Animal Health's (OIE) definition of animal welfare accounts for the health, comfort, and safety of the animals (Alonso et al. 2020) and has been proposed as an indicator for fly control. Disease incidence is the primary indicator for fly control because diseases such as pinkeye (conjunctivitis) and mastitis affect animal productivity. Keown and Kononoff (2007) found that poor udder health and mastitis result in annual losses of approximately US$200 per cow in dairy animals. Pinkeye infections are estimated to cause annual losses of US$150 million in beef and dairy production systems (Hansen 2001), which includes decreased growth rates of calves (Thrift and Overfield 1974, Ward and Nielson 1979). Cheng (1967) evaluated the frequency of pinkeye incidence in cattle and its association with face fly populations and found that cases of pinkeye consistently increased in herds of cattle where large numbers of face flies were recorded. This supports the need for producers to track disease incidence over time in their animals and include both fly populations and disease incidence in their decision making; the goal is to prevent disease rather than react to disease incidence.

While disease incidence is quantifiable, currently, it is difficult to assess animal welfare because there are few tools for assessing and measuring an animal's state of being (Cornish et al. 2016, Alonso et al. 2020). Fraser (2003) summarizes the methods of classifying animal welfare into three groups: objective, subjective, and natural living. These three groups focus on the animal's biological functions (e.g., health, well nourished), emotions (e.g., lacking stress and pain), and ability to express normal behaviors (e.g., laying, eating); combined the animal's environment should create a natural state for the species implying that welfare is 'an inherent characteristic of the animal and not of the environment' (Alonso et al. 2020). Broom (1986) discusses measuring welfare in terms of how the individual animal attempts to cope with its environment, while Fraser (2008) suggests that negative effects on animal welfare are demonstrated by a decrease in natural behaviors. These measurements include mortality rates, fertility, disease incidence, offspring number surviving and size, milk production, and growth rate. Other welfare indicators include heart rate, measures of adrenal outputs in the blood (e.g., cortisol), and abnormal animal behaviors such as decreased feeding (Broom 1986).

Cortisol levels are known to increase when an animal experiences stress (Whisnant et al. 1985, Boissy and Le Neindre 1997, González et al. 2003, Bristow and Holmes 2007, Mench et al. 2011). Stress occurs when environmental effects lead to the over taxation of animal control systems, resulting in adverse consequences and poor welfare (Broom 1983, 2001, 2007; Broom and Johnson 2000). Lindström et al. (2001) found that dairy cows with higher cortisol levels spent less time ruminating (Bristow and Holmes 2007). Vitela-Mendoza et al. (2016) examined the relationship between cortisol levels and defensive behaviors in dairy cattle exposed to stable flies and reported that cortisol levels are linearly related to the number of flies and frequency of defensive behaviors (e.g., more flies resulted in more defensive behaviors and cortisol). Schwinghammer et al. (1986) measured physiological and nutritional responses of beef steers exposed to horn flies and demonstrated that cortisol levels were significantly increased on the first day steers were exposed to 500 horn flies per head.

Current Practices

While a range of fly control options are available for the three major fly pests of beef cattle, decision making should also include how the

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

three fly populations interact and also how they affect the different livestock operations. This is especially important because fly control products and management practices for pasture cattle (cow-calf and stocker) are different than for confined animals (feedlot). In practice, we notice that cattle operators are not making pest management decisions on individual fly species, but rather flies as a group and some of the biggest obstacles are getting past the misconception that all flies impact their animals the same. Additionally, little research exists regarding how and when (i.e., at what pest population density or specific time within the calendar year) these control measures are implemented, and each farming operation can differ in producer or farm demographics, geographical location, animal selection and management, and producer perceptions.

Implementing a dynamic approach to monitor and control each fly species requires researchers to evaluate farm activities. Animal or crop production on a farm could influence pest fly populations. In 2007, about 35% of the 2.2 million farms in the U.S. reportedly owned beef cattle (U.S. Department of Agriculture, National Agricultural Statistics Service 2007, McBride and Mathews 2011); however, only 40% of the average farm produce value came from cattle production, and one-third of farm operators worked off-farm (McBride and Mathews 2011). A 2008 United States Department of Agriculture survey of US beef producers found that 16, 13, 14, and 78% of producers are also growing corn, soybeans, small grain crops, and hay, respectively (McBride and Mathews 2011). Here we speculate that a producer's management decisions (e.g., pest control methods, crop storage, etc.) for crop production and beef production, likely influence fly presence, abundance, and species diversity, and likely affect costs, expenses, and gains associated with animal productivity. For example, a farmer that is harvesting corn for silage will leave less than 1 m of stalk in the field, while a farmer that is harvesting corn for grain will likely leave the stalks and leaves in the field. The increased plant debris that are discarded at the grain site, compared to the silage site, could serve as a refuge for stable fly development, affecting fly growth, development, and population numbers. Moreover, flies developing in manure and animal waste can acquire and transfer mastitis-causing pathogens (Anderson et al. 2012). Producers are engaging in other cropping activities besides beef cattle production; however, farm profiles producing multiple commodities are underrepresented in the literature. Fly management options are limited in these integrated cropping systems, which likely have both food safety and biosecurity threats.

As a beef animal progresses through each sector (i.e., cow-calf, stocker, feedlot), there are more animals per operation, increasing animal density in each sector. In large feedlots (>10,000 animals per operations) an integrated approach to fly management is used. Over 96% of feedlots remove manure as part of their management program; this is foundational for fly control, and >30% are using a biological agent (parasitic wasps) for fly control (U.S. Department of Agriculture National Animal Health Monitoring System 2011, Machtinger et al. 2021). Despite these promising trends, over half of all feedlots surveyed use insecticide sprays as their primary fly management technique (U.S. Department of Agriculture National Animal Health Monitoring System 2011, Machtinger et al. 2021).

Producer perceptions influence the need to control filth flies. In a survey presented in McKay et al. (2019), Texas and Tennessee cow-calf producers were asked about the use of different horn fly management strategies. Producer data from that survey indicated they primarily apply insecticides to animals, and many other management strategies were never used or discontinued (not published). These producers also ranked pests based on perceived cost and damage, with filth flies ranked the highest (not published). McKay et al. (2019) also noted that willingness to use different management strategies varied based on demographics and perceptions. In addition to the response behaviors of livestock, disease presence, and fly numbers, producers' perceptions, demographics, and geography could be included in the development of a dynamic threshold.

Research Needs

There is a need to develop accurate methods and realistic models for assessing fly populations and developing a true surveillance program so producers can make informed decisions based on real-time data and its resulting predictions; the idea is to use precision agriculture technologies to build dynamic models that incorporate cumulative losses and expenses from multiple species and appropriate lag times.

Fly management decisions are typically focused on a single fly species and its individual effects on cattle; however, producers rarely find a single fly species on an animal, and most management options control more than one fly species to some extent. Future research should investigate each fly species as a part of the production system, rather than individually, in terms of sampling strategies and control methods. Catangui et al. (1997) noted that few thresholds are available for livestock pests. Economic thresholds should be developed for stable flies and updated for horn flies and face flies using validated and producer-approved monitoring methods in a dynamic surveillance system that weighs different fly densities by damage effects and costs. Updating ETs in a dynamic system would allow producers to implement changes that would help them make more informed decisions with their resources, time, and money when implementing control measures. Focusing on the flies as a dynamic system, rather than individually, would help researchers develop a more sustainable management program.

Using and Improving SMART (Sensors, Monitoring, Analysis, and Reporting Technologies) Surveillance to Make Informed Decisions

Current practice calls for producers to evaluate their animals in terms of the number of each fly species present, as well as occurrences of disease events; however, traditional monitoring methods (i.e., counting/visual inspection) are not feasible for many cattle operations. Producers need efficient methods, such as SMART traps used for pest and vector surveillance (Potamitis et al. 2017, Staunton et al. 2021). These SMART traps will allow producers to implement preventative measures, rather than react to emergent problems in their herds. For many of these fly species, it could be beneficial to monitor the animals' responses such as their fly-repelling behaviors (see Table 2) (Axtell 1981, Mullens et al. 2006, Machtinger et al. 2021). Easier approaches for producers could include the use of digital, thermal, or video imagery (Smythe et al. 2020, Psota et al. 2021). By using cameras, drones, cell phones, and/or game/stationary cameras, images could be taken of a percentage of the herd, and then uploaded to software (website/app) for analysis. Additionally, individual animal responses such as location, feeding, drinking, lying down, and tail flick can be monitored with sensors and also incorporated into the model (Barriuso et al. 2018, Oliveira et al. 2018, Martínez Rau et al. 2020, Herlin et al. 2021). Improvements in technology and computational analysis will provide automation and less labor-intensive fly monitoring and help producers make informed treatment decisions. These decisions could be based on calendar, animals' current market value, climate, environment, and/or costs of treatment approaches. Recently, beef producers from both extensive (cow-calf) and intensive (feedlots) systems from seven different

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

Table 2. Monitoring and management strategies for horn flies, face flies, and stable flies in the United States

IPM	Strategy	Horn Fly See (Brewer et al. 2021)	Face Fly (Trout Fryxell et al. 2021)	Stable Fly (Rochon et al. 2021)
Monitoring				
Fly Populations	Visual population counting	Cutkomp and Harvey 1958, Morgan 1964, Tugwell et al. 1969, Williams and Westby 1980, Skoda et al. 1987, Lysyk 2000, Smythe et al. 2020	McGuire and Sailer 1962, Hansens and Valiela 1967, Ode and Matthysse 1967, Williams and Westby 1980, Skoda et al. 1987	Bruce and Decker 1947, 1958; Cutkomp and Harvey 1958; Cheng and Kesler 1961; Campbell and Hermanussen 1971; Berry et al. 1983; Thomas et al. 1989; Guo et al. 1998; Mullens et al. 2006; Taylor et al. 2020
	Digital population counting	Smythe et al. 2020		
	Trap counting			Hogsette and Butler 1981; Berry et al. 1983; Thomas et al. 1989; Skoda et al. 1996; Guo et al. 1998; Taylor and Berkebile 2011; Taylor et al. 2013, 2020
	Immature population counting			Skoda et al. 1991, Berkebile et al. 1994, Talley et al. 2009, Taylor and Berkebile 2011, Wienhold and Taylor 2012, Albuquerque and Zurek 2014, Friesen et al. 2016
Animal Indicators	Tail flicking	Harvey and Launchbaugh 1982	Dougherty et al. 1993b	Todd 1964; Okumura 1977; Warnes and Finlayson 1987; Dougherty et al. 1993a,c, 1994, 1995; Mullens et al. 2006
	Leg stamping	Harvey and Launchbaugh 1982	Dougherty et al. 1993b	Todd 1964; Okumura 1977; Harris et al. 1987; Warnes and Finlayson 1987; Dougherty et al. 1993a,c, 1994; Mullens et al. 2006
	Head throwing	Harvey and Launchbaugh 1982	Dougherty et al. 1993b	Warnes and Finlayson 1987; Dougherty et al. 1993a,c, 1994, 1995; Mullens et al. 2006
	Skin twitching	Harvey and Launchbaugh 1982	Dougherty et al. 1993b	Dougherty et al. 1993a,c, 1994, 1995; Mullens et al. 2006
	Ear flicking		Harris et al. 1987, Dougherty et al. 1993b	Dougherty et al. 1993a,c, 1994, 1995
	Herd bunching		Dougherty et al. 1993b	Wieman et al. 1992, Dougherty et al. 1993c, Mullens et al. 2006

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

Table 2. Continued

IPM	Strategy	Horn Fly See (Brewer et al. 2021)	Face Fly (Trout Fryxell et al. 2021)	Stable Fly (Rochon et al. 2021)
Management				
Physical	Trapping *sticky *walk-thru *vacuum	Bruce 1938, Agee and Patterson 1983, Denning et al. 2014, Kienitz et al. 2018	Thimijan et al. 1973, Pickens et al. 1977, Kaya and Moon 1978, Peterson and Meyer 1978, Agee and Patterson 1983, Johnson and Campbell 1987, Denning et al. 2014, Kienitz et al. 2018	Bishopp 1913; Bailey et al. 1973; Thimijan et al. 1973; Williams 1973; Campbell and McNeal 1980; Berry et al. 1981; Rugg 1982; Agee and Patterson 1983; Gersabeck and Merritt 1983; Scholl 1986; Broce 1988; Zacks and Loew 1989; Hogsette and Ruff 1990; Mihok et al. 1995, 2006, 2007; Guo et al. 1998; Cilek 1999, 2003; Mihok 2002; Beresford and Sutcliffe 2006, 2008, 2017; Taylor and Berkebile 2006; Gilles et al. 2007; Taylor et al. 2007, 2013, 2017; Denning et al. 2014; Ose and Hogsette 2014; Dominghetti et al. 2015; Machtinger et al. 2016; Phasuk et al. 2016; Zhu et al. 2016; Hogsette and Kline 2017; Hogsette and Foil 2018; Kienitz et al. 2018
Cultural	Manure manipu-lation			Thomas et al. 1996
	Pasture design	Nichols et al. 2008		
Biological	Predators	Thomas and Morgan 1972, Legner 1978, Krantz 1983, Legner and Warkentin 1991, de Azevedo et al. 2015	Turner et al. 1968, Valiela 1969, Kessler and Balsbaugh 1972, Camp-bell and Hermanussen 1974, Wingo et al. 1974, Legner 1978, Thomas et al. 1983, Drummond et al. 1988	Legner and Brydon 1966, Legner and Olton 1970, Kessler and Balsbaugh 1972, Campbell and Hermanussen 1974, Smith et al. 1985, de Azevedo et al. 2018
	Competitors	Nichols et al. 2008, Fowler and Mullens 2016	Valiela 1969, Moon 1980, Nichols et al. 2008, Fowler and Mullens 2016	
	Parasitoids	Marlatt 1910, Hammer 1941, Peck 1974, Watts and Combs 1977, Figg et al. 1983, Cervenka and Moon 1991, Mendes and Linhares 1999, Geden et al. 2006	Blickle 1961, Benson and Wingo 1963, Sanders and Dobson 1966, Thomas and Wingo 1968, Turner et al. 1968, Wylie 1973, Wingo et al. 1974, Figg et al. 1983, Cervenka and Moon 1991	Greene et al. 1989
	Entomopathogenic viruses	Ribeiro et al. 2019	Geden et al. 2011	
	Entomopathogenic bacteria	Lysyk et al. 2010; Madhav et al. 2020a,b	Hower and Cheng 1968	Lysyk et al. 2002, 2010, 2012; Lysyk and Selinger 2012
	Entomopathogenic fungi	Steenberg et al. 2001; Angel-Sahagún et al. 2005; Lohmeyer and Miller 2006; Zimmermann 2008; Mochi et al. 2009, 2010a, b; Bawer et al. 2014; Galindo-Velasco et al. 2015; Holderman et al. 2017	Steenberg et al. 2001	Moraes et al. 2008, Cruz-Vazquez et al. 2015, Machtinger et al. 2016, Weeks et al. 2017
	Entomopathogenic nematodes	Trout Fryxell et al. 2021	Stoffolano and Nickle 1966, Stoffolano 1970, Thomas et al. 1972, Briggs and Milligan 1977, Kaya and Moon 1978, Kaya et al. 1979, Krafsur et al. 1983, Chirico 1990, Soto et al. 2014	Clark 2001, Mahmoud et al. 2007, Pierce 2012, Leal et al. 2017

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

Table 2. Continued

IPM	Strategy	Horn Fly See (Brewer et al. 2021)	Face Fly (Trout Fryxell et al. 2021)	Stable Fly (Rochon et al. 2021)
Chemical	Air projected capsules	See Brewer et al. 2021	Casida 1956, Kearns 1956, O'Brien 1963, 1966, Elliott and Janes 1978, Campbell 1981, Vijverberg et al. 1982, Casida et al. 1983, Coats 1990, Bloomquist 1996, Martin 1997, Thompson 1999, Geary 2005, Lynagh and Lynch 2012	
	Dust	See Brewer et al. 2021	Casida 1956; O'Brien 1963, 1966; Elliott and Janes 1978; Vijverberg et al. 1982; Casida et al. 1983; Coats 1990; Thompson 1999	
	Injection	See Brewer et al. 2021	Sommer et al. 1992	
	Ear tag	See Brewer et al. 2021	Casida 1956; O'Brien 1963, 1966; Elliott and Janes 1978; Campbell 1981; Vijverberg et al. 1982; Casida et al. 1983; Gaaboub and Hayes 1984a, b; Coats 1990; Bloomquist 1996; Martin 1997; Mulla and Su 1999; Thompson 1999; Geary 2005; Lynagh and Lynch 2012	
	Spray	Galindo-Velasco et al. 2015, See Brewer et al. 2021	Sun and Johnson 1960, Elliott and Janes 1978, Vijverberg et al. 1982, Casida et al. 1983, Coats 1990, Cox 2002, Isman 2006, Cloyd et al. 2009, Arnason et al. 2012, Khater 2012	
	Pour-on	See Brewer et al. 2021	Elliott and Janes 1978, Vijverberg et al. 1982, Casida et al. 1983, Coats 1990	
	Feed-through	Gingrich 1965, Mochi et al. 2009, See Brewer et al. 2021	Casida 1956, Kearns 1956, O'Brien 1963, 1966, Miura et al. 1976, Grosscurt 1978, Mayer et al. 1980, Thompson 1999, Matsumura 2010	Gingrich 1965
	Natural Biopesticides	Kraus et al. 1985; Miller and Chamberlain 1989; Isman 1999, 2000; Mulla and Su 1999; Enan 2001; Kostyukovsky et al. 2002; Akhtar and Isman 2004; Alexenizer and Dorn 2007; Mullens et al. 2009, 2017; Juan et al. 2011; Khater 2012; Klauck et al. 2014, 2015; Lachance and Grange 2014; Zhu et al. 2015, 2018; Mullens et al. 2018a; Mullens et al. 2018b	Gaaboub and Hayes 1984a, b; Mulla and Su 1999; Woolley et al. 2018	Miller and Chamberlain 1989; Feaster et al. 2009; Mullens et al. 2009; Zhu et al. 2009, 2010, 2011, 2012, 2014, 2018; Hieu, Kim, Kwon, et al. 2010; Hieu, Kim, Lee, et al. 2010; Baldacchino et al. 2013; Hieu et al. 2015; Showler 2017; Roh et al. 2020
	Larvicide/Substrate Treatment			Liu et al. 2012, Lohmeyer and Pound 2012, Taylor et al. 2012, Lohmeyer et al. 2014, Taylor et al. 2014, Donahue Jr et al. 2017
	Adulticide			Foil and Younger 2006, Hogsette et al. 2008, Nagagi et al. 2017
Genetic Modification	Flies themselves		Geden and Hogsette 1994	
	Host animals	Steelman et al. 1991 Tugwell et al. 1969, Holroyd et al. 1984, Stear et al. 1984, Brethour et al. 1987, Cocke et al. 1989, Brown et al. 1992, Steelman et al. 1996, Pruett et al. 2003, Untalan et al. 2006, Oliveira et al. 2013, Ling et al. 2020		
	Sterilization	Eschle et al. 1973, 1977, Kunz et al. 1974		

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

states identified that precision ranching through sensor-driven technology would be the most adaptable strategy to increase the sustainability of beef operations (Spiegal et al. 2020). Technology is already used to improve efficiencies in intensive animal systems (Neethirajan 2017) and real-time analysis of animal behavior, animal movement, as well as water utilization are currently being assessed in the arid southwest of the U.S. by using technology to address sustainability issues (Spiegal et al. 2020). Developing and evaluating new technologies for measuring and assessing these variables (parameters) are needed.

Once parameters can be estimated, management decisions by producers would incorporate precision agriculture tools to build a dynamic model that incorporates cumulative costs from multiple fly species over a given period of time. Equation (1) is an example of this dynamic approach for total fly costs in a herd of size n cattle once flies pass the EIL:

$$TFC_t = \sum_{i=1}^{n} c_{i,t}^{HF} + c_{i,t}^{FF} + c_{i,t}^{SF} \quad (1)$$

where TFC represents the total fly costs ($) in time period, t, obtained by summing over the animals with index i ($i = 1,\ldots,n$), where $c_{i,t}$ gives the costs imposed by the superscripted respective fly (HF is horn fly, FF is face fly, and SF is stable fly). While equation (1) is basic in form, it is difficult to estimate the costs from each respective fly species. Fly costs include losses from production efficiency, expenditures from control measures, and reductions in animal welfare. Examples of losses in production efficiency include, but are not limited to, reduced average daily gain, disease damages, and treatment costs (e.g., pinkeye). Control measure expenditures include items such as the cost of labor for treating flies and the cost of insecticides. The optimal control measures which would maximize profits for a producer are not known ex ante since one does not know the effectiveness of the control measures and how many flies will be present in a given season on a given animal. Furthermore, this amount would vary significantly across many variables such as herd, breed, and location. Finally, animal welfare costs could include consumers paying less for meat produced from certain production practices (e.g., meat treated with antibiotics, grass/pasture fed).

To estimate the costs in equation (1), each producer would need to quantify each of these terms for each animal, i, which would be extremely difficult. To begin these estimates, a producer could record their cost of fly control measures at the herd level and convert this into a \$/head estimate. Similarly, to estimate the cost of an associated fly-related disease such as pinkeye, the producer could estimate the cost of treatment per animal. Using data from biometric sensors could help approximate the costs to the producer arising from reduced average daily gain costs. For example, first the producer would estimate how the average daily gain was reduced by the respective fly (species, density, or complex), then they would estimate the amount of extra time and feed needed to finish out the animal and how much less the animal weighed at the time of its sale; conversion ratios could be determined with biometric sensors. Then, the producer would include data-associated feed and sale prices to determine how much this 'cost' is to the producer. While it would be difficult for the producer to accurately know which fly species was responsible for each aspect of these costs, it is possible for producers to record these costs and for technologies to be developed to help collect fly data to estimate total fly populations and associated costs. The costs should depend on the changing dynamics of the populations represented through mathematical models; where the most significant cost would be preventing death loss and additional losses could include those associated with animal efficiency.

Incorporating Animal Welfare Parameters into Decision-Based Models

Monitoring animal health and welfare outcomes is an often-overlooked component for developing and improving ETs for pest management unique to livestock pests and would enhance the development of pest management programs. Specifically, fly populations, disease incidence rates, and assessments for animal well-being should be incorporated in threshold development. This includes occurrences of diseases, longevity of outbreaks, and changes in animal well-being and natural expression. As a health example, although fly management is not necessary for a few face flies, their populations in the presence of pinkeye would warrant management to limit pathogen spread and disease exposure to all animal populations. Similarly, an animal that continues in its natural state – feeding and growing, but covered in horn flies – does not need fly management as the animal is tolerating the fly population. For emotional state, an animal could be bitten by stable flies but not reacting to pain (e.g., not stomping) and maintaining cortisol levels (e.g., not stressed). These examples reinforce the need to evaluate fly populations and animal health outcomes as a system in different environments and on different animals, rather than individually. This would account for the systemic impact of flies collectively and would consider impacts on health and welfare as part of a holistic animal system. When incorporating welfare into surveillance models, it is also important to understand the heterogeneity of the animal population, the environment, and the producer's needs to ensure best animal outcomes and cost efficiency.

Increasing Use and Efficacy of Biorational Insecticides Including Botanicals

Biorational insecticides could replace or supplement synthetic insecticides which could reduce the safety concerns and sustainability challenges through insecticide resistance around food animal products (Khan et al. 2008, Isman 2020). Before the development of synthetic compounds, plant extracts had a long use history and these extracts have multiple insecticidal and behavior-modifying properties, including behavioral effects, repellency, fumigant, and contact toxicity (Isman 2006). Multiple botanical extracts, such as pyrethrum, neem, and lemon eucalyptus oil, have been commercialized as insecticidal and repellent active ingredients (Isman 2006). Several essential oils significantly reduced horn fly and stable fly populations on cattle through contact and fumigant toxicities, repellency, and effects on fly mating rate and oviposition (Zhu et al. 2011, Mullens et al. 2017, Galli et al. 2018). Additionally, essential oils can act as synergists with conventional insecticides to reduce the insecticide dose and therefore reduce the risk of resistance development (Arena et al. 2018, Norris et al. 2018, Suwannayod et al. 2019). Showler (2017) summarized the effects of botanical products against both horn flies and stable flies. One attractive aspect of using botanicals and biorational insecticides, relative to many synthetics, is their biodegradability and lower mammalian toxicity, which makes botanical insecticides an alternative to synthetics where chemicals are applied in close proximity to animals (Pavela 2014). These products could also be used in a push-pull fly management strategy where flies are pushed from animals identified as resistant or treated with a repellent to targeted animals that are treated with a biorational insecticide. Their use also has the potential to reduce costs in pest management as integration of botanical insecticides with synthetic or biological insecticides could reduce the cost of chemicals and application compared to the use of synthetic insecticides alone (Ouma et al. 2014).

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

Research needs for using botanical products include enhancing their environmental stability, as they typically have shorter protective periods in field conditions. Research on using nanotechnology to formulate botanical insecticides has provided a new route to increase environmental stability (de Oliveira et al. 2018). Another barrier is commercialization and distribution of new botanical insecticides, which requires continuous plant availability, standardized products, and regulatory approval (Isman 2006). Plant growth highly depends on natural factors; therefore, extra steps are necessary to ensure consistency of products. An increase in the demand for biorational insecticides may improve production economics and stabilize consistency and availability of the raw materials needed to make these types of products.

Assessing the Role of Climate on Animal Production

In the U.S., greenhouse gas (GHG) emissions associated with agriculture are relatively small (10%) compared to electricity (25%), transportation (29%), industry (23%), and commercial and residential properties (13%); specifically cattle are associated with ~5% of U.S. GHG emissions (U.S. Environmental Protection Agency 2021). Over the last 20 yr, research activity on GHG emissions from livestock, with methane as a primary focus, has revolved around topics such as diet composition (Harper et al. 1999, McGinn et al. 2004), feed intake (Nkrumah et al. 2006, Goopy et al. 2020), feed efficiency, and feeding behaviors (Nkrumah et al. 2006). All these parameters form a complicated matrix that is often used to create predictive models of GHG emissions from beef cattle. Biting flies may contribute to GHG emissions through reduced average daily gains (Derouen et al. 1995), reduced feed efficiency (Campbell et al. 1987), and other metrics of productivity, and are currently left out of these predictive models. Animals may have increased GHG production by requiring more feed to get to market weight due to stress induced by biting flies. In some cases, biting fly control can improve weight gains by significant amounts (e.g., 17% increased gains in fly-controlled cattle vs. non-fly-controlled cattle in Derouen et al. (1995), 50% increased gains observed in Sanson et al. (2003)). But fly infestations can have thresholds where their control does not equate to increased productivity (Lysyk and Colwell 1996). It is imperative that sustainable pest management systems find a middle ground between productivity and GHG emission mitigation if one exists. Yet, many questions remain unanswered, including how flies affect residual feed intake, which has shown to be positively correlated with daily methane production (Nkrumah et al. 2006). How diet, location, climate, cattle breeds, cattle age, and other factors interact with fly burdens and how those relationships in turn affect GHG emissions is complex; thus it is important that GHG emission effects are included in data-driven models.

When considering the recent complete life cycle assessment of the entire beef industry, the Integrated Farm System Model (IFSM) can be used to determine the economic and environmental outcomes, which can include production costs, net returns, GHG emissions, energy use, and water consumption (Rotz et al. 2019). We propose the use of these parameters with fly management models. Results from the IFSM demonstrated that the majority of GHG emissions (~70%) came from the cow-calf sector (Rotz et al. 2019); however, little to no work in the area of cattle affected by fly pests as it relates to GHG emissions has been done. Additionally, the finishing sectors of the beef industry (stockers and feedlots) are contributing to just under 50% of all reactive nitrogen losses mainly in the form of ammonia emissions (Rotz et al. 2019). It is evident that more research is needed to determine the impact of fly pests on resource use such as water consumption and GHG emission rates from fly-infested animals versus those with few to no flies.

Fly Response to Warming Climate

Knowing flies are ectothermic and that their populations are dependent on climate, increased and/or fluctuating temperatures and rainfall will alter pest population densities and predator densities (Teskey 1969). Recently in Oklahoma, horn fly and face fly populations emerged earlier and had a longer season when there was a significant deviation of early spring warming compared to the five-year temperature mean (Scasta et al. 2017). Additionally, temperature highs reported for the day were the most influential variable as the high temperature for the day also increased horn fly numbers (Scasta et al. 2017). This was different for face flies as important variables included temperature three weeks prior, high temperatures, and days with precipitation predicted face fly populations (Scasta et al. 2017). In Florida, stable fly populations and their parasitoids were monitored weekly at equine facilities for three years and populations of both varied with temperature and precipitation (Pitzer et al. 2011). Follow up studies on house flies and parasitoids under fluctuating temperatures revealed increased abilities for flies to adapt to climate and limited abilities for their parasitoids to adapt, suggesting that with increased or variable climate, fly populations could become even more of a concern than current conditions (Geden et al. 2019, Biale et al. 2020). The role of fly predation on animal agriculture may also increase with warming climate.

Data-Driven and Dynamic Pest Modeling

Using data about the effects of pests on specific losses and expenses allows data-driven mathematical models to be developed that represent corresponding biological mechanisms. Including data associated with animal welfare, use of synthetic and/or biological insecticides, development of SMART sensors, and climatic considerations, can also provide suggestions of likely outcomes for different management strategies. Interventions (e.g., application to reduce fly numbers) can be incorporated as terms in these mathematical models and formulated as time-varying controls. Optimization tools, in particular application of optimal control techniques to ordinary differential equations, have been used successfully to suggest management strategies to achieve desired goals (Lenhart and Workman 2007). These techniques are formal, mathematical methods which can numerically find a control action (represented by functions of time and possibly space) in a given mathematical model that achieves a desired goal. Optimal control techniques have been applied successfully to a variety of pest management scenarios (Gaff et al. 2007, Whittle et al. 2007, Martinez et al. 2015, Guiver et al. 2016). In practice, the objective of minimizing costs to cattle given a fixed budget for control interventions is combined with a mathematical model for the population dynamics to formulate an optimal control solution. Given an appropriately parameterized model, the numerical techniques will compute the optimal control action and the corresponding population solution. The optimal control output then specifies a time-dependent IPM plan for minimizing both cost and loss within budget constraints. The type of mathematical model could vary from ordinary differential equations (continuous in time) to difference equations (discrete in time), and then later be extended to include spatial or age structure features as needed.

Ongoing pest population monitoring in a structured surveillance program provides a means to dynamically update the mathematical models and respond to both predictable and unpredictable events. In this context, the optimal control strategy or IPM plan described above is formulated based on the most likely sequence of events and the corresponding expected response to treatment. Mathematically, this is accomplished using a maximum likelihood estimation for the parameters

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

of the model based on data, and it can be continuously updated as new data become available with a corresponding update in the IPM plan. Another more complex approach involves mathematically modeling outcomes as probabilistic events with surveillance data updating the probabilities in a Bayesian setting (Ellison 2004). In this case, it may be possible to formulate optimal control plans that hedge against less likely scenarios with outsized potential for loss.

Conclusions

Filth flies negatively impact beef cattle production. Economic entomology allows researchers to focus on the economic feasibility of pest control methods and the use of IPM tactics allows producers to consider the long-term sustainability of pest management programs. Our literature review revealed that there is a dearth of research regarding the sustainability of fly management in animal production. Future research to develop dynamic ETs for flies affecting production systems, which incorporates animal welfare, economics, impacts of chemical use, and climate-related responses, would provide a foundation for the development of sustainable pest management programs similar to those being developed and implemented for crops. Dynamic and sustainable models will aid both small and large farms, as strategies that are effective for large operations typically are not feasible for small operations. There is an immediate need for improved monitoring methods that look at flies as a system and how all types collectively, rather than individually, shape the system for surveillance. This includes the addition of assessing and including animal defense behaviors, making it easier for producers to collect pest data; perhaps through the use of biological sensors. Finally, economic losses caused by each fly should be updated to account for losses due to animal defensive behaviors and reduced feed efficiency, as well as the unplanned expenditures associated with flies. One intention with this review is to argue for the critical need to develop smarter, producer-approved, sustainable fly management strategies for all animal production, and that without these strategies, animal production will remain inefficient and dependent upon chemical control. Moreover, we hope that the argument for preventative strategies and increased surveillance will help producers offset losses and expenses associated with filth flies and animal production.

Acknowledgments

We would like to recognize the reviewers of this manuscript and thank the following people for providing edits to initial drafts of the manuscript: Drs. Gary Brewer, Jerry Hogsette, Roger Moon, Amy Murillo, Pia Olafson, Kateryn Rochon, Doug Ross, and David Taylor. We thank the members of the S1076 regional hatch project: Fly management in animal agriculture systems and impacts on animal health and food safety for manuscript discussion and advice. Additionally, we greatly appreciate the financial support from Penn State Extension grant to hold a workshop in Orlando, Florida, for the discussion of this manuscript and others in the series. This multi-state Extension work was supported by the USDA National Institute of Food and Agriculture Extension Smith Lever funding under Project PEN04540 and Accession 1000356.

References Cited

Agee, H. R., and R. S. Patterson. 1983. Spectral sensitivity of stable, face, and horn flies and behavioral responses of stable flies to visual traps (Diptera: Muscidae). Environ. Entomol 12: 1823–1828.

Akhtar, Y., and M. B. Isman. 2004. Comparative growth inhibitory and antifeedant effects of plant extracts and pure allelochemicals on four phytophagous insect species. J. Appl. Entomol 128: 32–38.

Albuquerque, T. A., and L. Zurek. 2014. Temporal changes in the bacterial community of animal feces and their correlation with stable fly oviposition, larval development, and adult fitness. Front. Microbiol 5: 590.

Alexenizer, M., and A. Dorn. 2007. Screening of medicinal and ornamental plants for insecticidal and growth regulating activity. J. Pest. Sci 80: 205–215.

Alonso, M. E., J. R. González-Montaña, and J. M. Lomillos. 2020. Consumers' concerns and perceptions of farm animal welfare. Animals 10: 385–398.

Anderson, K. L., R. Lyman, K. Moury, D. Ray, D. W. Watson, and M. T. Correa. 2012. Molecular epidemiology of *Staphylococcus aureus* mastitis in dairy heifers. J. Dairy Sci 95: 4921–4930.

Angel-Sahagún, C. A., R. Lezama-Gutiérrez, J. Molina-Ochoa, E. Galindo-Velasco, M. López-Edwards, O. Rebolledo-Domínguez, C. Cruz-Vázquez, W. P. Reyes-Velázquez, S. R. Skoda, and J. E. Foster. 2005. Susceptibility of biological stages of the horn fly, *Haematobia irritans,* to entomopathogenic fungi (*Hyphomycetes*). J. Insect Sci 5: 50–58.

Arena, J. S., A. B. Omarini, M. P. Zunino, M. L. Peschiutta, M. T. Defagó, and J. A. Zygadlo. 2018. Essential oils from *Dysphania ambrosioides* and *Tagetes minuta* enhance the toxicity of a conventional insecticide against *Alphitobius diaperinus*. Ind. Crops Prod 122: 190–194.

Arnason, J. T., S. R. Sims, and I. M. Scott. 2012. Natural products from plants as insecticides. United Nations Educational, Scientific, and Cultural Organization and Encycl. Life Support Syst (EOLSS). 1–8. https://www.eolss.net/Sample-Chapters/C06/E6-151-13.pdf

Arther, R. 1991. Management of horn fly resistance. Mobay Animal Health, Shawnee, KS.

Axtell, R. C. 1981. Livestock integrated pest management (IPM): principles and prospects, pp. 31–40. *In* F. W. Knapp (ed.), Systems approach to animal health and production. University of Kentucky, Lexington.

de Azevedo, L. H., R. M. Emberson, F. de C. N. Esteca, and G. J. de Moraes. 2015. Macrochelid mites (Mesostigmata: Macrochelidae) as biological control agents, pp. 103–132. *In* D. Carrillo, G. J. de Moraes, and J. E. Peña (eds.), Prospects biol. control plant feed. Mites harmful org., progress in biological control. Springer International Publishing, Cham.

de Azevedo, L. H., M. P. Ferreira, R. de C. Castilho, P. H. D. Cançado, and G. J. de Moraes. 2018. Potential of *Macrocheles* species (Acari: Mesostigmata: Macrochelidae) as control agents of harmful flies (Diptera) and biology of *Macrocheles embersoni* Azevedo, Castilho and Berto on *Stomoxys calcitrans* (L.) and *Musca domestica* L. (Diptera: Muscidae). Biol. Control 123: 1–8.

Bailey, D. L., T. L. Whitfield, and B. J. Smittle. 1973. Flight and dispersal of the stable fly. J. Econ. Entomol 66: 410–411.

Baldacchino, F., V. Muenworn, M. Desquesnes, F. Desoli, T. Charoenviriyaphap, and G. Duvallet. 2013. Transmission of pathogens by *Stomoxys* flies (Diptera, Muscidae): a review. Parasite 20: 26.

Barriuso, A. L., G. Villarrubia González, J. F. De Paz, Á. Lozano, and J. Bajo. 2018. Combination of multi-agent systems and wireless sensor networks for the monitoring of cattle. Sensors 18: 108.

Bawer, M. D., P. E. D'Souza, and B. S. Pradeep. 2014. Biocontrol of *Haematobia irritans* horn flies with entomopathogenic fungi (*Beauveria bassiana* and *Metarhizium anisopliae*). J. Biol. Control 28: 112–114.

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

Beresford, D. V., and J. F. Sutcliffe. 2006. Studies on the effectiveness of coroplast sticky traps for sampling stable flies (Diptera: Muscidae), including a comparison to alsynite. J. Econ. Entomol 99: 1025–1035.

Beresford, D. V., and J. F. Sutcliffe. 2008. Stable fly (*Stomoxys calcitrans*: Diptera, Muscidae) trap response to changes in effective trap height caused by growing vegetation. J. Vector Ecol 33: 40–45.

Beresford, D. V., and J. F. Sutcliffe. 2017. Evidence for sticky-trap avoidance by stable fly, *Stomoxys calcitrans* (Diptera: Muscidae), in response to trapped flies. J. Am. Mosq. Control Assoc 33: 250–252.

Berkebile, D. R., G. D. Thomas, and J. B. Campbell. 1994. Overwintering of the stable fly (Diptera: Muscidae) in southeastern Nebraska. J. Econ. Entomol 87: 1555–1563.

Berry, I. L., P. J. Scholl, and J. I. Shugart. 1981. A mark and recapture procedure for estimating population sizes of adult stable flies. Environ. Entomol 10: 88–93.

Berry, I. L., D. A. Stage, and J. B. Campbell. 1983. Populations and economic impacts of stable flies on cattle. Trans. ASAE 26: 873–877.

Biale, H., C. J. Geden, and E. Chiel. 2020. Heat adaptation of the house fly (Diptera: Muscidae) and its associated parasitoids in Israel. J. Med. Entomol 57: 113–121.

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

Bishopp, F. C. 1913. The stable fly (*Stomoxys calcitrans* L.), an important livestock Pest. J. Econ. Entomol 6: 112–126.

Blickle, R. L. 1961. Parasites of the face fly, *Musca autumnalis*, in New Hampshire. J. Econ. Entomol 54: 802.

Bloomquist, J. R. 1996. Ion channels as targets for insecticides. Annu. Rev. Entomol 41: 163–190.

Boissy, A., and P. Le Neindre. 1997. Behavioral, cardiac and cortisol responses to brief peer separation and reunion in cattle. Physiol. Behav 61: 693–699.

Brethour, J. R., T. L. Harvey, R. Negus, L. Corah, and D. Patterson. 1987. Effect of cattle breed and flucythrinate-impregnated ear tags on horn fly (Diptera: Muscidae) control on yearling heifers. J. Econ. Entomol 80: 1035–1038.

Brewer, G. J., D. J. Boxler, L. D. Domingues, R. T. Trout Fryxell, C. Holderman, K. M. Loftin, E. Machtinger, B. Smythe, J. L. Talley, and W. Watson. 2021. Horn fly (Diptera: Muscidae)—biology, management, and future research directions. J. Integr. Pest Manag 12: 42.

Briggs, J., and S. E. Milligan. 1977. Pathogens of *Musca domestica* and *M. autumnalis* (houseflies and face flies). Bull. World Health Organ 55: 245.

Bristow, D. J., and D. S. Holmes. 2007. Cortisol levels and anxiety-related behaviors in cattle. Physiol. Behav 90: 626–628.

Broce, A. B. 1988. An improved alsynite trap for stable flies, *Stomoxys calcitrans* (Diptera: Muscidae). J. Med. Entomol 25: 406–409.

Broom, D. 1983. The stress concept and ways of assessing the effects of stress in farm animals. Appl. Anim. Ethol 11: 79.

Broom, D. M. 1986. Indicators of poor welfare. Br. Vet. J142: 524–526.

Broom, D. 2001. Coping, stress and welfare, pp. 1–9. *In* D. M. Broom (ed.), Coping with Challenge; Welfare in Animals Including Humans, Proceedings of Dahlem Conference. Dahlem University Press, Berlin.

Broom, D. 2007. Quality of life means welfare: how is it related to other concepts and assessed? Anim. Welf 16(S): 45–53.

Broom, D., and K. Johnson. 2000. Stress and animal welfare, 2nd ed. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Brown, A. H., Jr., C. D. Steelman, Z. B. Johnson, C. F. Rosenkrans Jr., and T. M. Brasuell. 1992. Estimates of repeatability and heritability of horn fly resistance in beef cattle. J. Anim. Sci 70: 1375–1381.

Bruce, W. G. 1938. A practical trap for the control of horn flies on cattle. J. Kans. Entomol. Soc 11: 88–93.

Bruce, W. N., and G. C. Decker. 1947. Fly control and milk flow. J. Econ. Entomol 40: 530–536.

Bruce, W. N., and G. C. Decker. 1958. The relationship of stable fly abundance to milk production in dairy cattle. J. Econ. Entomol 51: 269–274.

Campbell, W. C. 1981. An introduction to the avermectins. N. Z. Vet. J 29: 174–178.

Campbell, J. B., and I. L. Berry. 1989. Economic threshold for stable flies on confined livestock. Misc. Publ. Entomol. Soc. Am 74: 18–22.

Campbell, J. B., and J. F. Hermanussen. 1971. Efficacy of insecticides and methods of insecticidal application for control of stable flies in Nebraska. J. Econ. Entomol 64: 1188–1190.

Campbell, J. B., and J. F. Hermanussen. 1974. *Philonthus theveneti*: life history and predatory habits against stable flies, house flies, and face flies under laboratory conditions. Environ. Entomol 3: 356–358.

Campbell, J., and C. McNeal. 1980. A guide to integrated pest management at feedlots and dairies. Hist. Mater. Univ. Neb.-Linc. Ext.

Campbell, J. B., I. L. Berry, D. J. Boxler, R. L. Davis, D. C. Clanton, and G. H. Deutscher. 1987. Effects of stable flies (Diptera: Muscidae) on weight gain and feed efficiency of feedlot cattle. J. Econ. Entomol 80: 117–119.

Casida, J. E. 1956. Mode of action of pesticides, metabolism of organophosphorus insecticides in relation to their antiesterase activity, stability, and residual properties. J. Agric. Food Chem 4: 772–785.

Casida, J. E., D. W. Gammon, A. H. Glickman, and L. J. Lawrence. 1983. Mechanisms of selective action of pyrethroid insecticides. Annu. Rev. Pharmacol. Toxicol 23: 413–438.

Catangui, M. A., J. B. Campbell, G. D. Thomas, and D. J. Boxler. 1997. Calculating economic injury levels for stable flies (Diptera: Muscidae) on feeder heifers. J. Econ. Entomol 90: 6–10.

Cervenka, V. J., and R. D. Moon. 1991. Arthropods associated with fresh cattle dung pats in Minnesota. J. Kans. Entomol. Soc 64: 131–145.

Cheng, T.-H. 1967. Frequency of pinkeye incidence in cattle in relation to face fly Abundance. J. Econ. Entomol 60: 598–599.

Cheng, T.-H., and E. M. Kesler. 1961. A three-year study on the effect of fly control on milk production by selected and randomized dairy herds. J. Econ. Entomol 54: 751–757.

Chirico, J. 1990. Sex ratio, emergence and infection rates of *Heterotylenchus*-exposed *Musca autumnalis* (Diptera: Muscidae). J. Parasitol 76: 124–127.

Christensen, J. 2001. Epidemiological concepts regarding disease monitoring and surveillance. Acta Vet. Scand 42: S11.

Cilek, J. E. 1999. Evaluation of various substances to increase adult *Stomoxys calcitrans* (Diptera: Muscidae) collections on alsynite cylinder traps in North Florida. J. Med. Entomol 36: 605–609.

Cilek, J. E. 2003. Attraction of colored plasticized corrugated boards to adult stable flies, *Stomoxys calcitrans* (Diptera: Muscidae). Fla. Entomol 86: 420–423.

Clark, B. 2001. Virulence and persistence of entomopathogenic nematodes toward filth flies in cattle feedlot manure. M.S. Thesis, University of Nebraska Lincoln, NE.

Cloyd, R. A., C. L. Galle, S. R. Keith, N. A. Kalscheur, and K. E. Kemp. 2009. Effect of commercially available plant-derived essential oil products on arthropod pests. J. Econ. Entomol 102: 1567–1579.

Coats, J. R. 1990. Mechanisms of toxic action and structure-activity relationships for organochlorine and synthetic pyrethroid insecticides. Environ. Health Perspect 87: 255–262.

Cocke, J., R. Knutson, and D. K. Lunt. 1989. Effects of horn fly control with λ-cyhalothrin ear tags on weight gains in weaning calves in Texas. Southwest. Entomol 14: 357–362.

Cornish, A., D. Raubenheimer, and P. McGreevy. 2016. What we know about the public's level of concern for farm animal welfare in food production in developed countries. Animals 6: 74.

Cox, C. 2002. Insecticide fact sheet: Pyrethrins/Pyrethrum. J. Pesticide Reform 22: 14–20.

Cruz-Vazquez, C., J. Carvajal Márquez, R. Lezama-Gutiérrez, I. Vitela-Mendoza, and M. Ramos-Parra. 2015. Efficacy of the entomopathogenic fungi *Metarhizium anisopliae* in the control of infestation by stable flies *Stomoxys calcitrans* (L.), under natural infestation conditions. Vet. Parasitol 212: 350–355.

Cupp, M. S., E. W. Cupp, C. Navarre, D. Zhang, X. Yue, L. Todd, and V. Panagala. 2010. Salivary gland thrombostasin isoforms differentially regulate blood uptake of horn flies fed on control- and thrombostasin-vaccinated cattle. J. Med. Entomol 47: 610–617.

Cutkomp, L. K., and A. L. Harvey. 1958. The weight responses of beef cattle in relation to control of horn and stable flies. J. Econ. Entomol 51: 72–75.

Denning, S. S., S. P. Washburn, and D. W. Watson. 2014. Development of a novel walk-through fly trap for the control of horn flies and other pests on pastured dairy cows. J. Dairy Sci 97: 4624–4631.

Derouen, S. M., L. D. Foil, J. W. Knox, and J. M. Turpin. 1995. Horn fly (Diptera: Muscidae) control and weight gains of yearling beet cattle. J. Econ. Entomol 88: 666–668.

Dominghetti, T. F. de S., A. T. M. de Barros, C. O. Soares, P. H. D. Cançado, T. F. de S. Dominghetti, A. T. M. de Barros, C. O. Soares, and P. H. D. Cançado. 2015. *Stomoxys calcitrans* (Diptera: Muscidae) outbreaks: current situation and future outlook with emphasis on Brazil. Rev. Bras. Parasitol. Veterinária 24: 387–395.

Domingues, L. N., K. G. Bendele, L. Halos, Y. Moreno, C. Epe, M. Figueiredo, M. Liebstein, and F. D. Guerrero. 2021. Identification of anti-horn fly vaccine antigen candidates using a reverse vaccinology approach. Parasites Vectors 14: 442.

Donahue, W. A. Jr, A. T. Showler, M. W. Donahue, B. E. Vinson, and W. L. Osbrink. 2017. Lethal effects of the insect growth regulator cyromazine against three species of filth flies, *Musca domestica*, *Stomoxys calcitrans*, and *Fannia canicularis* (Diptera: Muscidae) in cattle, swine, and chicken manure. J. Econ. Entomol 110: 776–782.

Dougherty, C., F. Knapp, P. Burrus, D. Willis, P. Cornelius, and N. Bradley. 1993a. Multiple releases of stable flies (*Stomoxys calcitrans* L.) and behaviour of grazing beef cattle. Appl. Anim. Behav. Sci 38: 191–212.

Dougherty, C. T., F. W. Knapp, P. B. Burrus, D. C. Willis, and N. W. Bradley. 1993b. Face flies (*Musca autumnalis* De Geer) and the behavior of grazing beef cattle. Appl. Anim. Behav. Sci 35: 313–326.

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

Dougherty, C. T., F. W. Knapp, P. B. Burrus, D. C. Willis, J. G. Burg, and P. L. Cornelius. 1993c. Stable flies (*Stomoxys calcitrans* L.) and the behavior of grazing beef cattle. Appl. Anim. Behav. Sci 35: 215–233.

Dougherty, C. T., F. W. Knapp, P. B. Burrus, D. C. Willis, and P. L. Cornelius. 1994. Moderation of grazing behavior of beef cattle by stable flies (*Stomoxys calcitrans* L.). Appl. Anim. Behav. Sci 40: 113–127.

Dougherty, C. T., F. W. Knapp, P. B. Burrus, D. C. Willis, and P. L. Cornelius. 1995. Behavior of grazing cattle exposed to small populations of stable flies (*Stomoxys calcitrans* L.). Appl. Anim. Behav. Sci 42: 231–248.

Drummond, R. O., G. Lambert, H. E. J. Smalley, and C. E. Terrill. 1981. Estimated losses of livestock to pests, pp. 111–127. *In* Pimentel D. (ed.) CRC Handbook of Pest Management in Agriculture. Agric. CRC Press Inc, Boca Raton, FL.

Drummond, R. O., J. E. George, and S. E. Kunz. 1988. Control of arthropod pests of livestock: a review of technology. CRC Press Inc, Boca Raton, FL.

Elliott, M., and N. Janes. 1978. Synthetic pyrethroids–a new class of insecticide. Chem. Soc. Rev 7: 473–505.

Ellison, A. 2004. Bayesian inference in ecology. Ecol. Lett 7: 509–520.

Enan, E. 2001. Insecticidal activity of essential oils: octopaminergic sites of action. Comp. Biochem. Physiol. Part C Toxicol. Pharmacol 130: 325–337.

Engelken, T. J. 2008. Developing replacement beef heifers, pp. 569–572. *In* Theriogenology, Proceedings of the Annual Conference of the Society for Theriogenology, vol. 70.

Eschle, J. L., S. E. Kunz, C. D. Schmidt, B. F. Hogan, and R. O. Drummond. 1973. Suppression of a population of horn flies with the sterile-male technique. Environ. Entomol 2: 976–980.

Eschle, J. L., J. A. Miller, and C. D. Schmidt. 1977. Insect growth regulator and sterile males for suppression of horn flies. Nature. 265: 325–326.

Feaster, J. E., M. A. Scialdone, R. G. Todd, Y. I. Gonzalez, J. P. Foster, and D. L. Hallahan. 2009. Dihydronepetalactones deter feeding activity by mosquitoes, stable flies, and deer ticks. J. Med. Entomol 46: 832–840.

Figg, D. E., R. D. Hall, and G. D. Thomas. 1983. Insect parasites associated with Diptera developing in bovine dung pats on central Missouri pastures. Environ. Entomol 12: 961–966.

Foil, L. D., and C. D. Younger. 2006. Development of treated targets for controlling stable flies (Diptera: Muscidae). Vet. Parasitol 137: 311–315.

Fowler, F. E., and B. A. Mullens. 2016. Dividing the pie: differential dung pat size utilization by sympatric *Haematobia irritans* and *Musca autumnalis*. Med. Vet. Entomol 30: 185–192.

Fraser, D. 2003. Assessing animal welfare at the farm and group level: the interplay of science and values. Anim. Welfare. 12: 433–443.

Fraser, D. 2008. Understanding animal welfare. Acta Vet. Scand 50: S1.

Friesen, K., D. Berkebile, B. Wienhold, L. Durso, J. Zhu, and D. B. Taylor. 2016. Environmental parameters associated with stable fly (Diptera: Muscidae) development at hay feeding sites. Environ. Entomol 45: 570–576.

Gaaboub, I. A., and D. K. Hayes. 1984a. Biological activity of azadirachtin, component of the neem tree inhibiting molting in the face fly, *Musca autumnalis* De Geer (Diptera: Muscidae). Environ. Entomol 13: 803–812.

Gaaboub, I. A., and D. K. Hayes. 1984b. Effect of larval treatment with azadirachtin, a molting inhibitory component of the neem tree, on reproductive capacity of the face fly, *Musca autumnalis* De Geer (Diptera: Muscidae). Environ. Entomol 13: 1639–1643.

Gaff, H., H. R. Joshi, and S. Lenhart. 2007. Optimal harvesting during an invasion of a sublethal plant pathogen. Environ. Dev. Econ 12: 673–686.

Galindo-Velasco, E., R. Lezama-Gutiérrez, C. Cruz-Vázquez, A. Pescador-Rubio, C. A. Angel-Sahagún, M. M. Ojeda-Chi, R. I. Rodríguez-Vivas, and D. Contreras-Lara. 2015. Efficacy of entomopathogenic fungi (Ascomycetes: Hypocreales) against adult *Haematobia irritans* (Diptera: Muscidae) under stable conditions in the Mexican dry tropics. Vet. Parasitol 209: 173–178.

Galli, G. M., L. F. Roza, R. C. V. Santos, P. M. Quatrin, A. F. Ourique, B. Klein, R. Wagner, M. D. Baldissera, A. Volpato, G. Campigotto, *et al.* 2018. Low dose of nanocapsules containing eucalyptus oil has beneficial repellent effect against horn fly (Diptera: Muscidae). J. Econ. Entomol 111: 2983–2987.

Geary, T. G. 2005. Ivermectin 20 years on: maturation of a wonder drug. Trends Parasitol 21: 530–532.

Geden, C., and J. Hogsette. 1994. Research and extension needs for integrated pest management for arthropods of veterinary importance. Proceedings of a workshop in Lincoln, Nebraska, April 12–14, 1994. Last updated October 2001.

Geden, C. J., R. D. Moon, and J. F. Butler. 2006. Host ranges of six solitary filth fly parasitoids (Hymenoptera: Pteromalidae, Chalcididae) from Florida, Eurasia, Morocco, and Brazil. Environ. Entomol 35: 405–412.

Geden, C. J., T. Steenberg, V.-U. Lietze, and D. G. Boucias. 2011. Salivary gland hypertrophy virus of house flies in Denmark: prevalence, host range, and comparison with a Florida isolate. J. Vector Ecol 36: 231–238.

Geden, C. J., H. Biale, E. Chiel, and D. M. Johnson. 2019. Effect of fluctuating high temperatures on house flies (Diptera: Muscidae) and their principal parasitoids (*Muscidifurax* spp. and *Spalangia* spp. [Hymenoptera: Pteromalidae]) from the United States. J. Med. Entomol 56: 1650–1660.

Gerry, A. C. 2018. Cattle ectoparasites in extensive and intensive cattle systems, pp. 39–50. *In* T. Engle, J. Kingborg, **and** B. E. Roll (eds.), Welf. cattle. CRC Press, Boca Raton, FL, USA.

Gersabeck, E. F., and R. W. Merritt. 1983. Vertical and temporal aspects of Alsynite panel sampling for adult *Stomoxys calcitrans* (L.) (Diptera: Muscidae). Fla. Entomol 66: 222–227.

Gilles, J., J.-F. David, G. Duvallet, S. D. L. Rocque, and E. Tillard. 2007. Efficiency of traps for *Stomoxys calcitrans* and *Stomoxys niger niger* on Reunion Island. Med. Vet. Entomol 21: 65–69.

Gingrich, R. E. 1965. *Bacillus thuringiensis* as a feed additive to control Dipterous pests of cattle. J. Econ. Entomol 58: 363–364.

González, M., A. K. Yabuta, and F. Galindo. 2003. Behaviour and adrenal activity of first parturition and multiparous cows under a competitive situation. Appl. Anim. Behav. Sci 83: 259–266.

Goopy, J. P., D. Korir, D. Pelster, A. I. M. Ali, S. E. Wassie, E. Schlecht, U. Dickhoefer, L. Merbold, and K. Butterbach-Bahl. 2020. Severe below-maintenance feed intake increases methane yield from enteric fermentation in cattle. Br. J. Nutr 123: 1239–1246.

Gordon, D. V., W. O. Haufe, and K. K. Klein. 1984. Determination of economic thresholds for horn fly control in Western Canada: a farm level simulation approach. .Can. J. Agric. Econ. Rev. Can. Econ. Rural. 32: 399–421.

Greene, G. L., J. A. Hogsette, and R. S. Patterson. 1989. Parasites that attack stable fly and house fly (Diptera: Muscidae) puparia during the winter on dairies in Northwestern Florida. J. Econ. Entomol 82: 412–415.

Grosscurt, A. C. 1978. Diflubenzuron: some aspects of its ovicidal and larvicidal mode of action and an evaluation of its practical possibilities. Pestic. Sci 9: 373–386.

Guiver, C., C. Edholm, Y. Jin, M. Mueller, J. Powell, R. Rebarber, B. Tenhumberg, and S. Townley. 2016. Simple adaptive control for positive linear systems with applications to pest management. SIAM J. Appl. Math 76: 238–275.

Guo, Y.-J., G. L. Greene, and M. D. Butine. 1998. Population profile of stable flies (Diptera: Muscidae) caught on alsynite traps in various feedlot habitats. J. Econ. Entomol 91: 159–164.

Hammer, O. 1941. Biological and ecological investigations on flies associated with pasturing cattle and their excrement. Vidensk Mead Dan. Naturh Foren 105: 141–393.

Hansen, R. 2001. New tools in the battle against pinkeye. *In* Nevada. Livest Prod Annu Update, vol. 5(8).

Hansens, E. J., and I. Valiela. 1967. Activity of the face fly in New Jersey. J. Econ. Entomol 60: 26–28.

Harper, L. A., O. T. Denmead, J. R. Freney, and F. M. Byers. 1999. Direct measurements of methane emissions from grazing and feedlot cattle. J. Anim. Sci 77: 1392–1401.

Harris, J. A., J. E. Hillerton, and S. V. Morant. 1987. Effect on milk production of controlling muscid flies, and reducing fly-avoidance behaviour, by the use of Fenvalerate ear tags during the dry period. J. Dairy Res 54: 165–171.

Harvey, T. L., and J. L. Launchbaugh. 1982. Effect of horn flies on behavior of cattle. J. Econ. Entomol 75: 25–27.

Headley, J. C. 1972. Defining the economic threshold. *In*, pp. 100–108. *In* Pest Control Strategies for the Future. Washington DC: Nat. Acad. Sci.

Herlin, A., E. Brunberg, J. Hultgren, N. Högberg, A. Rydberg, and A. Skarin. 2021. Animal welfare implications of digital tools for monitoring and management of cattle and sheep on pasture. Animals. 11: 829.

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

Hieu, T. T., S. Kim, H. W. Kwon, and Y. Ahn. 2010. Enhanced repellency of binary mixtures of *Zanthoxylum piperitum pericarp* steam distillate or *Zanthoxylum armatum* seed oil constituents and *Calophyllum inophyllum* nut oil and their aerosols to *Stomoxys calcitrans*. Pest Manag. Sci 66: 1191–1198.

Hieu, T. T., S.-I. Kim, S.-G. Lee, and Y.-J. Ahn. 2010. Repellency to *Stomoxys calcitrans* (Diptera: Muscidae) of plant essential oils alone or in combination with *Calophyllum inophyllum* nut oil. J. Med. Entomol 47: 575–580.

Hieu, T. T., W. S. Choi, S. Kim, M. Wang, and Y. Ahn. 2015. Enhanced repellency of binary mixtures of *Calophyllum inophyllum* nut oil fatty acids or their esters and three terpenoids to *Stomoxys calcitrans*. Pest Manag. Sci 71: 1213–1218.

Hogsette, J. A., and J. F. Butler. 1981. Field and laboratory devices for manipulation of pupal parasites. Presented at the Workshop on Status of Biological Control of Filth Flies, Gainesville, Fla. (USA), 4–5 Feb 1981. Science and Education Administration.

Hogsette, J. A., and L. D. Foil. 2018. Blue and black cloth targets: effects of size, shape, and color on stable fly (Diptera: Muscidae) attraction. J. Econ. Entomol 111: 974–979.

Hogsette, J. A., and D. L. Kline. 2017. The Knight stick trap and Knight stick sticky wraps: new tools for stable fly (Diptera: Muscidae) management. J. Econ. Entomol 110: 1384–1389.

Hogsette, J. A., and J. P. Ruff. 1990. Comparative attraction of four different fiberglass traps to various age and sex classes of stable fly (Diptera: Muscidae) adults. J. Econ. Entomol 83: 883–886.

Hogsette, J. A., A. Nalli, and L. D. Foil. 2008. Evaluation of different insecticides and fabric types for development of treated targets for stable fly (Diptera: Muscidae) control. J. Econ. Entomol 101: 1034–1038.

Holderman, C. J., L. A. Wood, C. J. Geden, and P. E. Kaufman. 2017. Discovery, development, and evaluation of a horn fly-isolated (Diptera: Muscidae) *Beauveria bassiana* (Hypocreales: Cordyciptaceae) strain from Florida, USA. J. Insect Sci 17: 51.

Holroyd, R. G., D. J. Hirst, A. W. Merrifield, and M. A. Toleman. 1984. The effect of spraying for buffalo fly (*Haematobia irritans exigua*) on infestations, growth rate and lesion development on *Bos indicus* × *B. taurus* cattle in the dry tropics of north Queensland. Aust. J. Agric. Res 35: 595–608.

Hower, A. A., Jr., and T.-H. Cheng. 1968. Inhibitive effect of *Bacillus thuringiensis* on the development of the face fly in cow manure. J. Econ. Entomol 61: 26–31.

International Society of Precision Agriculture. 2021. Precision Ag Definition. https://www.ispag.org/about/definition.

Isman, M. B. 2000. Plant essential oils for pest and disease management. Crop Prot., XIVth International Plant Protection Congress 19: 603–608.

Isman, M. B. 2006. Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. Annu. Rev. Entomol 51: 45–66.

Isman, M. B. 2020. Botanical insecticides in the twenty-first century—fulfilling their promise? Annu. Rev. Entomol 65: 233–249.

Isman, M. (University of B. C.) 1999. Pesticides based on plant essential oils. Pestic. Outlook, U. K.

Johnson, G. D., and J. B. Campbell. 1987. Evaluation of sticky traps for collecting face flies (Diptera: Muscidae) from different locations in an irrigated pasture. Environ. Entomol 16: 190–194.

Juan, L. W., A. Lucia, E. N. Zerba, L. Harrand, M. Marco, and H. M. Masuh. 2011. Chemical composition and fumigant toxicity of the essential oils from 16 species of eucalyptus against *Haematobia irritans* (Diptera: Muscidae) adults. J. Econ. Entomol 104: 1087–1092.

Kaya, H. K., and R. D. Moon. 1978. The nematode *Heterotylenchus autumnalis* and face fly *Musca autumnalis*: a field study in Northern California. J. Nematol 10: 333–341.

Kaya, H. K., R. D. Moon, and P. L. Witt. 1979. Influence of the nematode, *Heterotylenchus autumnalis*, on the behavior of face fly, *Musca autumnalis*. Environ. Entomol 8: 537–540.

Kearns, C. 1956. The mode of action of insecticides. Annu. Rev. Entomol 1: 123–148.

Keown, J. F., and P. J. Kononoff. 2007. How to Interpret the DHIA-520 somatic cell count profile. University of Nebraska-Lincoln Extension, Institute of Agriculture and Natural Resources, in line from http://www. extension.unl.edu/publications.(Consulta 19-08-08).

Kessler, H., and E. U. Balsbaugh Jr. 1972. Succession of adult Coleoptera in bovine manure in east central South Dakota. Ann. Entomol. Soc. Am 65: 1333–1336.

Khan, A., A. H. Sayyed, M. Aslam, M. Razaq, G. Jilani, and M. A. Saleem. 2008. Evidence of field-evolved resistance to organophosphates and pyrethroids in *Chrysoperla carnea* (Neuroptera: Chrysopidae). J. Econ. Entomol 101: 1676–1684.

Khater, H. 2012. Prospects of botanical biopesticides in insect pest management. Pharmacologia 3: 641–656.

Kienitz, M. J., B. J. Heins, and R. D. Moon. 2018. Evaluation of a commercial vacuum fly trap for controlling flies on organic dairy farms. J. Dairy Sci 101: 4667–4675.

Klauck, V., R. Pazinato, L. M. Stefani, R. C. Santos, R. A. Vaucher, M. D. Baldissera, R. Raffin, A. Boligon, M. Athayde, D. Baretta, *et al.* 2014. Insecticidal and repellent effects of tea tree and andiroba oils on flies associated with livestock. Med. Vet. Entomol 28: 33–39.

Klauck, V., R. Pazinato, W. Radavelli, A. Volpato, L. Stefani, C. R, R. Vaucher, A. Boligon, M. Linde Athayde, and A. Silva. 2015. In vitro repellent effect of tea tree (*Melaleuca alternifolia*) and andiroba (*Carapa guianensis*) oils on *Haemotobia irritans* and *Chrysomya megacephala* flies. Trop. Biomed 32: 160–6.

Kostyukovsky, M., A. Rafaeli, C. Gileadi, N. Demchenko, and E. Shaaya. 2002. Activation of octopaminergic receptors by essential oil constituents isolated from aromatic plants: possible mode of action against insect pests. Pest Manag. Sci 58: 1101–1106.

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

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

Krantz, G. W. 1983. Mites as biological control agents of dung-breeding flies, with special reference to the Macrochelidae. Biol. Control Pests Mites 91–98: 3304.

Kraus, W., M. Bokel, A. Klenk, and H. Pöhn. 1985. The structure of azadirachtin and 22,23-dihydro-23β-methoxyazadirachtin. Tetrahedron Lett 26: 6435–6438.

Kunz, S. E., M. R. Graham, B. F. Hogan, and J. L. Eschle. 1974. Effect of releases of sterile horn flies into a native population of horn flies. Environ. Entomol 3: 159–162.

Kunz, S. E., K. D. Murrell, G. Lambert, L. F. James, and C. E. Terrill. 1991. Estimated losses of livestock to pests, pp. 69–98. *In* Pimentel D. (ed.) CRC Handbook of Pest Management in Agriculture. Agric. CRC Press Inc, Boca Raton, FL.

Lachance, S., and G. Grange. 2014. Repellent effectiveness of seven plant essential oils, sunflower oil and natural insecticides against horn flies on pastured dairy cows and heifers. Med. Vet. Entomol 28: 193–200.

Lawrence, J. D., and M. A. Ibarburu. 2007. Economic analysis of pharmaceutical technologies in modern beef production (No. 37560), 2007 Conf. April 16–17 2007 Chic. Ill., 2007 Conference, April 16–17, 2007, Chicago, Illinois. NCCC-134 Conference on Applied Commodity Price Analysis, Forecasting, and Market Risk Management.

Leal, L. C. de S. R., C. M. de O. Monteiro, A. É. de Mendonça, V. R. E. P. Bittencourt, and A. J. Bittencourt. 2017. Potential of entomopathogenic nematodes of the genus *Heterorhabditis* for the control of *Stomoxys calcitrans* (Diptera: Muscidae). Rev. Bras. Parasitol. Veterinária 26: 451–456.

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.). Proc. Pap. Forty-Sixth Annu. Conf. Calif. Mosq. Vector Control Assoc. Inc., January 29–Febr. 1 1978, Held Ahwahnee Hotel Yosemite Calif.

Legner, E. F., and H. W. Brydon. 1966. Suppression of dung-inhabiting fly populations by pupal parasites. Ann. Entomol. Soc. Am 59: 638–651.

Legner, E. F., and G. S. Olton. 1970. Worldwide survey and comparison of adult predator and scavenger insect populations associated with domestic animal manure where livestock is artificially congregated. Hilgardia. 40: 225–266.

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

Legner, E. F., and R. W. Warkentin. 1991. Influence of Onthophagus gazella on hornfly, Haematobia irritans density in irrigated pastures. Entomophaga. 36: 547–553.

Lenhart, S., and J. T. Workman. 2007. Optimal control applied to biological models. Chapman and Hall/CRC, New York.

Lindström, T., I. Redbo, and K. Uvnäs-Moberg. 2001. Plasma oxytocin and cortisol concentrations in dairy cows in relation to feeding duration and rumen fill. Physiology & Behavior. 72: 73–81.

Ling, A., T. Krause, B. Heins, N. Hinkle, D. Pringle, S. E. Aggrey, and R. Rekaya. 2020. Genetic study of horn fly abundance in beef cattle. J. Anim. Sci 98: 16–17.

Liu, S., A. Y. Li, K. H. Lohmeyer, and A. A. Perez De Leon. 2012. Effects of pyriproxyfen and buprofezin on immature development and reproduction in the stable fly. Med. Vet. Entomol 26: 379–385.

Lohmeyer, K. H., and J. A. Miller. 2006. Pathogenicity of three formulations of entomopathogenic fungi for control of adult *Haematobia irritans* (Diptera: Muscidae). J. Econ. Entomol 99: 1943–1947.

Lohmeyer, K., and J. Pound. 2012. Laboratory evaluation of novaluron as a development site treatment for controlling larval horn flies, house flies, and stable flies (Diptera: Muscidae). J. Med. Entomol 49: 647–651.

Lohmeyer, K., J. Pound, K. Yeater, and M. May. 2014. Efficacy of novaluron as a feed-through for control of immature horn flies, house flies, and stable flies (Diptera: Muscidae) developing in cow manure. J. Med. Entomol 51: 873–877.

Lynagh, T., and J. Lynch. 2012. Molecular mechanisms of Cys-loop ion channel receptor modulation by ivermectin. Front. Mol. Neurosci 5: 60.

Lysyk, T. J. 2000. Comparison of sample units for estimating population abundance and rates of change of adult horn fly (Diptera: Muscidae). J. Med. Entomol 37: 299–307.

Lysyk, T. J., and D. D. Colwell. 1996. Duration of efficacy of diazinon ear tags and ivermectin pour-on for control of horn fly (Diptera: Muscidae). J. Econ. Entomol 89: 1513–1520.

Lysyk, T. J., and L. B. Selinger. 2012. Effects of temperature on mortality of larval stable fly (Diptera: Muscidae) caused by five isolates of *Bacillus thuringiensis*. J. Econ. Entomol 105: 732–737.

Lysyk, T. J., L. D. Kalischuk-Tymensen, and L. B. Selinger. 2002. Comparison of selected growth media for culturing *Serratia marcescens*, *Aeromonas* sp., and *Pseudomonas aeruginosa* as pathogens of adult *Stomoxys calcitrans* (Diptera: Muscidae). J. Med. Entomol 39: 89–98.

Lysyk, T. J., L. D. Kalischuk-tymensen, K. Rochon, and L. B. Selinger. 2010. Activity of *Bacillus thuringiensis* isolates against immature horn fly and stable fly (Diptera: Muscidae). J. Econ. Entomol 103: 1019–1029.

Lysyk, T. J., L. D. Kalischuk-Tymensen, and L. B. Selinger. 2012. Mortality of adult *Stomoxys calcitrans* fed isolates of *Bacillus thuringiensis*. J. Econ. Entomol 105: 1863–1870.

Machtinger, E. T., A. C. Gerry, A. C. Murillo, and J. L. Talley. 2021. Filth fly impacts to animal production in the United States and associated research and Extension needs. J. Integr. Pest Manag 12: 41, 1–13.

Machtinger, E. T., N. C. Leppla, and J. A. Hogsette. 2016. House and stable fly seasonal abundance, larval development substrates, and natural parasitism on small equine farms in Florida. Neotrop. Entomol 45: 433–440.

Machtinger, E. T., E. N. I. Weeks, and C. J. Geden. 2016. Oviposition deterrence and immature survival of filth flies (Diptera: Muscidae) when exposed to commercial fungal products. J. Insect Sci 16.

Madhav, M., G. Brown, J. A. Morgan, S. Asgari, E. A. McGraw, and P. James. 2020a. Transinfection of buffalo flies (*Haematobia irritans exigua*) with *Wolbachia* and effect on host biology. Parasit. Vectors. 13: 1–14.

Madhav, M., G. Brown, J. A. Morgan, S. Asgari, E. A. McGraw, U. G. Munderloh, T. J. Kurtti, and P. James. 2020b. *Wolbachia* successfully replicate in a newly established horn fly, *Haematobia irritans irritans* (L.) (Diptera: Muscidae) cell line. Pest Manag. Sci. 76: 2441–2452.

Mahmoud, M. F., N. S. Mandour, and Y. I. Pomazkov. 2007. Efficacy of the entomopathogenic nematode *Steinernema feltiae* cross N 33 against larvae and pupae of four fly species in the laboratory. Nematol. Mediterr.

Marlatt, C. L. 1910. The horn fly (Haematobia serrata Rob.-Desv.). U.S. Dept. Agr. Bur. Entomol. Circ. 115. 13 p.

Martin, R. 1997. Modes of action of anthelmintic drugs. Vet. J 154: 11–34.

Martinez, M. V., S. Lenhart, and K. J. White. 2015. Optimal control of integrodifference equations in a pest-pathogen system. Discrete Contin. Dyn. Syst.-B 20: 1759.

Martínez Rau, L., J. O. Chelotti, S. R. Vanrell, and L. L. Giovanini. 2020. Developments on real-time monitoring of grazing cattle feeding behavior using sound, pp. 771–776. *In* 2020 IEEE Int. Conf. Ind. Technol. ICIT. Presented at the 2020 IEEE International Conference on Industrial Technology (ICIT).

Matsumura, F. 2010. Studies on the action mechanism of benzoylurea insecticides to inhibit the process of chitin synthesis in insects: a review on the status of research activities in the past, the present and the future prospects. Pestic. Biochem. Physiol 97: 133–139.

Mayer, R. T., S. M. Meola, D. L. Coppage, and J. R. DeLoach. 1980. Utilization of imaginal tissues from pupae of the stable fly for the study of chitin synthesis and screening of chitin synthesis inhibitors. J. Econ. Entomol 73: 76–80.

McBride, W. D., and K. Mathews. 2011. The diverse structure and organization of U.S. beef cow-calf farms. USDA ERS. http://www.ers.usda.gov/publications/pub-details/?pubid=44532.

McGinn, S. M., K. A. Beauchemin, T. Coates, and D. Colombatto. 2004. Methane emissions from beef cattle: effects of monensin, sunflower oil, enzymes, yeast, and fumaric acid. J. Anim. Sci 82: 3346–3356.

McGuire, J. U., and R. I. Sailer. 1962. A method of estimating face fly populations on cattle. Vol. 33. U. S. Department of Agriculture, Agricultural Research Service.

McInerney, J. P., K. S. Howe, and J. A. Schepers. 1992. A framework for the economic analysis of disease in farm livestock. Prev. Vet. Med 13: 137–154.

McKay, L., K. L. DeLong, S. Schexnayder, A. P. Griffith, D. B. Taylor, P. Olafson, and R. T. Trout Fryxell. 2019. Cow-calf producers' willingness to pay for bulls resistant to horn flies (Diptera: Muscidae). J. Econ. Entomol 112: 1476–1484.

Mench, J. A., J. C. Swanson, and W. R. Stricklin. 2011. Social stress and dominance among group members after mixing beef cows. Can. J. Anim. Sci.

Mendes, J., and A. X. Linhares. 1999. Diapause, pupation sites and parasitism of the horn fly, *Haematobia irritans*, in south-eastern Brazil. Med. Vet. Entomol 13: 185–190.

Mihok, S. 2002. The development of a multipurpose trap (the Nzi) for tsetse and other biting flies. Bull. Entomol. Res 92: 385–403.

Mihok, S., E. K. Kang'ethe, and G. K. Kamau. 1995. Trials of traps and attractants for *Stomoxys* spp. (Diptera: Muscidae). J. Med. Entomol 32: 283–289.

Mihok, S., D. A. Carlson, E. S. Krafsur, and L. D. Foil. 2006. Performance of the Nzi and other traps for biting flies in North America. Bull. Entomol. Res 96: 387–397.

Mihok, S., D. A. Carlson, and P. N. Ndegwa. 2007. Tsetse and other biting fly responses to Nzi traps baited with octenol, phenols and acetone. Med. Vet. Entomol 21: 70–84.

Miller, A. J., and W. F. Chamberlain. 1989. Azadirachtin as a larvicide against the horn fly, stable fly, and house fly (Diptera: Muscidae). J. Econ. Entomol 82: 1375–1378.

Miura, T., C. H. Schaefer, R. M. Takahashi, and F. S. Mulligan III. 1976. Effects of the insect growth inhibitor, Dimilin, on hatching of mosquito eggs. J. Econ. Entomol 69: 655–658.

Mochi, D. A., A. C. Monteiro, L. D. Simi, and A. A. M. Sampaio. 2009. Susceptibility of adult and larval stages of the horn fly, *Haematobia irritans*, to the entomopathogenic fungus *Metarhizium anisopliae* under field conditions. Vet. Parasitol 166: 136–143.

Mochi, D. A., A. C. Monteiro, A. C. R. Machado, and L. Yoshida. 2010a. Entomopathogenic fungal activity against pupae and adult *Haematobia irritans* (Diptera: Muscidae). Vet. Parasitol 168: 105–110.

Mochi, D. A., A. C. Monteiro, A. C. R. Machado, and L. Yoshida. 2010b. Efficiency of entomopathogenic fungi in the control of eggs and larvae of the horn fly *Haematobia irritans* (Diptera: Muscidae). Vet. Parasitol 167: 62–66.

Moon, R. D. 1980. Effects of larval competition on face fly. Environ. Entomol 9: 325–330.

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

Moon, R. D. 2019. Muscid flies (Muscidae),pp. 345–368. *In* G. R. Mullen, L. A. Durden (eds.), Med. Vet. Entomol. AP Academic Press, San Diego, CA.

Moraes, A. P. R., I. da C. Angelo, É. K. K. Fernandes, V. R. E. P. Bittencourt, and A. J. Bittencourt. 2008. Virulence of *Metarhizium anisopliae* to eggs and immature stages of *Stomoxys calcitrans*. Ann. N. Y. Acad. Sci 1149: 384–387.

Morgan, N. O. 1964. Autecology of the adult horn fly, *Haematobia irritans* (L.), (Diptera: Muscidae). Ecology. 45: 728–736.

Morris, R. 1997. How economically important is animal disease and why. pp 1 – 11. *In* A. A. Dijkhuizen **and** R. S. Morris (eds.), Anim. Health Econ. Princ. Appl. Post Grad. Found. Vet. Sci. Univ. Syd. S. Aust.

Mulla, M. S., and T. Su. 1999. Activity and biological effects of neem products against arthropods of medical and veterinary importance. Act. Biol. Eff. Neem Prod. Arthropods Med. Vet. Importance 15: 133–152.

Mullens, B. A., K.-S. Lii, Y. Mao, J. A. Meyer, N. G. Peterson, and C. E. Szijj. 2006. Behavioural responses of dairy cattle to the stable fly, *Stomoxys calcitrans*, in an open field environment. Med. Vet. Entomol 20: 122–137.

Mullens, B. A., W. G. Reifenrath, and S. M. Butler. 2009. Laboratory trials of fatty acids as repellents or antifeedants against houseflies, horn flies and stable flies (Diptera: Muscidae). Pest Manag. Sci 65: 1360–1366.

Mullens, B. A., D. W. Watson, A. C. Gerry, B. A. Sandelin, D. Soto, D. Rawls, S. Denning, L. Guisewite, and J. Cammack. 2017. Field trials of fatty acids and geraniol applied to cattle for suppression of horn flies, *Haematobia irritans* (Diptera: Muscidae), with observations on fly defensive behaviors. Vet. Parasitol 245: 14–28.

Mullens, B. A., D. Soto, and A. C. Gerry. 2018a. Sex ratios and mating status of the horn fly on pastured cattle as a function of repellent-oil treatments. J. Med. Entomol 55: 1325–1329.

Mullens, B. A., D. Soto, A. C. Gerry, F. E. Fowler, and A. N. Diniz. 2018b. Effects of fatty acid and geraniol repellent-oil mixtures applied to cattle on blood feeding and reproductive parameters in field populations of *Haematobia irritans* (Diptera: Muscidae). J. Med. Entomol 55: 408–416.

Nagagi, Y., V. Temba, and E. Komba. 2017. The efficacy of ZeroFly Screen, insecticide incorporated screen, against nuisance and biting flies on cattle kept under zero grazing system in the northern zone of Tanzania. Livest. Res Rural Dev 29: 3.

Nayduch, D., and R. G. Burris. 2017. Flourishing in filth: house fly – microbe interactions across life history. Annals of the Entomol. Soc. Of Am. 111: 6–18. https://academic.oup.com/aesa/article/110/1/6/2893406?login=true

Neethirajan, S. 2017. Recent advances in wearable sensors for animal health management. Sens. Bio-Sens. Res 12: 15–29.

Nichols, E., S. Spector, J. Louzada, T. Larsen, S. Amezquita, and M. E. Favila. 2008. Ecological functions and ecosystem services provided by Scarabaeinae dung beetles. Biol. Conserv 141: 1461–1474.

Nkrumah, J. D., E. K. Okine, G. W. Mathison, K. Schmid, C. Li, J. A. Basarab, M. A. Price, Z. Wang, and S. S. Moore. 2006. Relationships of feedlot feed efficiency, performance, and feeding behavior with metabolic rate, methane production, and energy partitioning in beef cattle1. J. Anim. Sci 84: 145–153.

Norris, R. F., E. P. Caswell-Chen, and M. Kogan. 2003. Concepts in integrated pest management, 1st ed. Prentice Hall, Upper Saddle River, N.J.

Norris, E. J., J. B. Johnson, A. D. Gross, L. C. Bartholomay, and J. R. Coats. 2018. Plant essential oils enhance diverse pyrethroids against multiple strains of mosquitoes and inhibit detoxification enzyme processes. Insects. 9: 132.

O'Brien, R. 1963. Mode of action of insecticides, binding of organophosphates to cholinesterases. J. Agric. Food Chem 11: 163–166.

O'Brien, R. 1966. Mode of action of insecticides. Annu. Rev. Entomol 11: 369–402.

Ode, P. E., and J. G. Matthysse. 1967. Bionomics of the face fly, *Musca autumnalis* DeGeer. (40). New Cornell Univ. Agri. Expt. Station, New York, USA, 91.

Okumura, T. 1977. The relationship of attacking fly abundance to behavioral responses of grazing cattle. Jpn. J. Appl. Entomol. Zool 21: 119–122.

Oliveira, M. C. S., M. M. Alencar, R. Giglioti, M. C. D. Beraldo, F. F. Aníbal, R. O. Correia, L. Boschini, A. C. S. Chagas, T. B. Bilhassi, and H. N. Oliveira. 2013. Resistance of beef cattle of two genetic groups to ectoparasites and gastrointestinal nematodes in the state of São Paulo, Brazil. Vet. Parasitol 197: 168–175.

Oliveira, B. R., M. N. Ribas, F. S. Machado, J. A. M. Lima, L. F. L. Cavalcanti, M. L. Chizzotti, and S. G. Coelho. 2018. Validation of a system for monitoring individual feeding and drinking behaviour and intake in young cattle. Animal 12: 634–639.

de Oliveira, J. L., E. V. Ramos Campos, and L. F. Fraceto. 2018. Recent developments and challenges for nanoscale formulation of botanical pesticides for use in sustainable agriculture. J. Agric. Food Chem 66: 8898–8913.

Onstad, D. W., and L. M. Knolhoff. 2009. Finding the economics in economic entomology. J. Econ. Entomol 102: 1–7.

Ose, G. A., and J. A. Hogsette. 2014. Spatial distribution, seasonality and trap preference of stable fly, *Stomoxys calcitrans* L. (Diptera: Muscidae), adults on a 12-hectare zoological park. Zoo Biol 33: 228–233.

Ouma, B., J. Muthomi, J. Nderitu, and F. Toroitich. 2014. Management of thrips in French bean by integrating biological and synthetic pesticides in conventional spray regimes. J. Renew. Agric 2: 27.

Oyzrzún M. P., A. Quiroz, and M. A. Birkett. 2008. Insecticide resistance in the horn fly: alternative control strategies. Med. Vet. Entomol 22: 188–202.

Pavela, R. 2014. Insecticidal properties of *Pimpinella anisum* essential oils against the *Culex quinquefasciatus* and the non-target organism *Daphnia magma*. J. Asia-Pac. Entomol 17: 287–293.

Peck, O. 1974. Chalcidoid (Hymenoptera) parasites of the horn fly, *Haematobia irritans* (Diptera: Muscidae), in Alberta and elsewhere in Canada. Can. Entomol 106: 473–477.

Peterson, R. D., II, and H. J. Meyer. 1978. Trapping technique for male face flies. J. Econ. Entomol 71: 40–42.

Phasuk, J., A. Prabaripai, and T. Chareonviriyaphap. 2016. A comparison of attractants for sampling *Stomoxys calcitrans* (Diptera: Muscidae) on dairy farms in Saraburi Province, Thailand. J. Econ. Entomol 109: 942–946.

Pickens, L. G., R. W. Miller, and J. J. Grasela. 1977. Sticky panels as traps for *Musca autumnalis*. J. Econ. Entomol 70: 549–552.

Pierce, L. R. 2012. Efficacy of entomopathogenic nematodes utilized for control of stable flies (*Stomoxys calcitrans*) at round bale feeding sites. M.S. Thesis, Oklahoma State University, Stillwater Oklahoma.

Pitzer, J. B., P. E. Kaufman, J. A. Hogsette, C. J. Geden, and S. H. Tenbroeck. 2011. Seasonal abundance of stable flies and filth fly pupal parasitoids (Hymenoptera: Pteromalidae) at Florida equine facilities. J. Econ. Entomol 104: 1108–1115.

Potamitis, I., P. Eliopoulos, and I. Rigakis. 2017. Automated remote insect surveillance at a global scale and the internet of things. Robotics. 6: 19.

Pruett, J. H., C. D. Steelman, J. A. Miller, J. M. Pound, and J. E. George. 2003. Distribution of horn flies on individual cows as a percentage of the total horn fly population. Vet. Parasitol 116: 251–258.

Psota, E. T., E. K. Luc, G. M. Pighetti, L. G. Schneider, R. T. Trout Fryxell, J. W. Keele, and L. A. Kuehn. 2021. Development and validation of a neural network for the automated detection of horn flies on cattle. Comput. Electron. Agric 180: 105927.

Rabb, R. L. 1972. Principles and concepts of pest management. *In* Implement. Pract. Pest Manag. Strateg. Proc. Natl. Ext. Insect Pest Manag. Workshop.

Ribeiro, J. M., H. J. Debat, M. Boiani, X. Ures, S. Rocha, and M. Breijo. 2019. An insight into the sialome, mialome and virome of the horn fly, *Haematobia irritans*. BMC Genomics. 20: 616.

Rochon, K., J. Hogsette, P. Kaufman, P. Olafson, S. Swiger, and D. Taylor. 2021. Stable fly (Diptera: Muscidae)—biology, management, and research needs. J. Integr. Pest Manag 12: 38.

Roh, G. H., X. Zhou, Y. Wang, S. C. Cermak, J. A. Kenar, A. Lehmann, B. Han, D. B. Taylor, X. Zeng, and C. G. Park. 2020. Spatial repellency, antifeedant activity and toxicity of three medium chain fatty acids and their methyl esters of coconut fatty acid against stable flies. Pest Manag. Sci 76: 405–414.

Rotz, C. A., S. Asem-Hiablie, S. Place, and G. Thoma. 2019. Environmental footprints of beef cattle production in the United States. Agric. Syst 169: 1–13.

Rugg, D. 1982. Effectiveness of Williams traps in reducing the numbers of stable flies (Diptera: Muscidae). J. Econ. Entomol 75: 857–859.

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

Rushton, J. 2009. The economics of animal health and production. CAB International, Cambridge, MA.

Sanders, D. P., and R. C. Dobson. 1966. The insect complex associated with bovine manure in Indiana. Ann. Entomol. Soc. Am 59: 955–959.

Sanson, D. W., A. A. DeRosa, G. R. Oremus, and L. D. Foil. 2003. Effect of horn fly and internal parasite control on growth of beef heifers. Vet. Parasitol 117: 291–300.

Scasta, J. D., J. L. Talley, D. M. Engle, and D. M. Debinski. 2017. Climate extremes, vegetation change, and decoupling of interactive fire-grazing processes exacerbate fly parasitism of cattle. Environ. Entomol 46: 191–200.

Schmidtmann, E. T., and M. E. Valla. 1982. Face-fly pest intensity, fly-avoidance behavior (bunching) and grazing time in Holstein heifers. Appl. Anim. Ethol 8: 429–438.

Scholl, P. J. 1986. Field population studies of *Stomoxys calcitrans* (L.) in eastern Nebraska. Southwest. Entomol. USA.

Schwinghammer, K. A., F. W. Knapp, J. A. Boling, and K. K. Schillo. 1986. Physiological and nutritional response of beef steers to infestations of the horn fly (Diptera: Muscidae). J. Econ. Entomol 79: 1010–1015.

Showler, A. T. 2017. Botanically based repellent and insecticidal effects against horn flies and stable flies (Diptera: Muscidae). J. Integr. Pest Manag 8: 15, 1–11.

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., and G. D. Thomas. 1993. Rural flies in the urban environment? 1–66.

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 Nebraska1. J. Econ. Entomol 80: 811–816.

Skoda, S. R., G. D. Thomas, and J. B. Campbell. 1991. Developmental sites and relative abundance of immature stages of the stable fly (Diptera: Muscidae) in beef cattle feedlot pens in Eastern Nebraska. J. Econ. Entomol 84: 191–197.

Skoda, S. R., G. D. Thomas, and J. B. Campbell. 1996. Comparison of core sampling and pupal traps for monitoring immature stable flies and house flies (Diptera: Muscidae) in beef feedlot pens. J. Econ. Entomol 89: 428–434.

Smith, J. P., R. D. Hall, and G. D. Thomas. 1985. Field studies on mortality of the immature stages of the stable fly (Diptera: Muscidae). Environ. Entomol. 14: 881–890.

Smith, K. V., K. L. DeLong, A. P. Griffith, C. N. Boyer, C. C. Martinez, S. M. Schexnayder, and R. T. Trout Fryxell. 2022. Costs of horn fly (Diptera: Muscidae) control for cow-calf producers in Tennessee and Texas, 2016. J. Econ. Entomol. 115: 371–380.

Smythe, B., D. Boxler, G. Brewer, E. Psota, and D. W. Watson. 2020. Using visual and digital imagery to quantify horn fly (Diptera: Muscidae) densities. J. Insect Sci 20: 16, 1–7.

Sommer, C., B. Steffansen, B. O. Nielsen, J. Grønvold, K.-M. V. Jensen, J. B. Jespersen, J. Springborg, and P. Nansen. 1992. Ivermectin excreted in cattle dung after subcutaneous injection or pour-on treatment: concentrations and impact on dung fauna. Bull. Entomol. Res 82: 257–264.

Soto, D., F. E. Fowler, B. A. Sandelin, and B. A. Mullens. 2014. *Musca autumnalis* (Diptera: Muscidae) and the host-specific nematode *Paraiotonchium autumnale* (Tylenchida: Iotonchiidae) in Southern California. J. Med. Entomol 51: 288–292.

Spiegal, S., A. F. Cibils, B. T. Bestelmeyer, J. L. Steiner, R. E. Estell, D. W. Archer, B. W. Auvermann, S. V. Bestelmeyer, L. E. Boucheron, H. Cao, *et al.* 2020. Beef production in the southwestern United States: strategies toward sustainability. Front. Sustain. Food Syst 4.

Staunton, K. M., J. E. Crawford, J. Liu, M. Townsend, Y. Han, M. Desnoyer, P. Howell, W. Xiang, T. R. Burkot, N. Snoad, *et al.* 2021. A low-powered and highly selective trap for male *Aedes* (Diptera: Culicidae) surveillance: the male *Aedes* sound trap. J. Med. Entomol 58: 408–415.

Stear, M. J., M. J. Newman, F. W. Nicholas, S. C. Brown, and R. G. Holroyd. 1984. Tick resistance and the major histocompatibility system. Aust. J. Exp. Biol. Med. Sci 62: 47–52.

Steelman, C. D., A. Hayden Brown jr., E. E. Gbur, and G. Tolley. 1991. Interactive response of the horn fly (Diptera: Muscidae) and selected breeds of beef cattle. J. Econ. Entomol 84: 1275–1282.

Steelman, C. D., C. J. Brown, R. W. McNew, E. E. Gbur, M. A. Brown, and G. Tolley. 1996. The effects of selection for size in cattle on horn fly population density. Med. Vet. Entomol 10: 129–136.

Steelman, C. D., R. W. McNew, R. B. Simpson, R. W. Rorie, J. M. Phillips, C. F. Rosenkrans Jr. 2003. Evaluation of alternative tactics for management of insecticide-resistant horn flies (Diptera: Muscidae). J. Econ. Entomol 96: 892–901.

Steenberg, T., J. B. Jespersen, K.-M. V. Jensen, B. O. Nielsen, and R. A. Humber. 2001. Entomopathogenic fungi in flies associated with pastured cattle in Denmark. J. Invertebr. Pathol 77: 186–197.

Stern, V., R. Smith, R. van den Bosch, and K. Hagen. 1959. The integration of chemical and biological control of the spotted alfalfa aphid: the integrated control concept. Hilgardia 29: 81–101.

Stoffolano, J. G. 1970. Parasitism of *Heterotylenchus autumnalis* Nickle (Nematoda: Sphaerulariidae) to the face fly, *Musca autumnalis* De Geer (Diptera: Muscidae). J. Nematol 2: 324–329.

Stoffolano, J. G., Jr., and W. R. Nickle. 1966. Nematode parasite (*Heterotylenchus* sp.) of face fly in New York State. J. Econ. Entomol 59: 221–222.

Sun, Y.-P., and E. Johnson. 1960. Synergistic and antagonistic actions of insecticide-synergist combinations and their mode of action. J. Agric. Food Chem 8: 261–266.

Suwannayod, S., K. L. Sukontason, B. Pitasawat, A. Junkum, K. Limsopatham, M. K. Jones, P. Somboon, R. Leksomboon, T. Chareonviriyaphap, A. Tawatsin, *et al.* 2019. Synergistic toxicity of plant essential oils combined with pyrethroid insecticides against blow flies and the house fly. Insects 10: 178–194.

Talley, J., and E. T. Machtinger. 2020. Livestock entomology. *In* J. H. Byrd **and** J. K. Tomberlin, Forensic entomol. util. arthropods leg. investig. CRC Press, Boca Raton, FL.

Talley, J., A. Broce, and L. Zurek. 2009. Characterization of stable fly (Diptera: Muscidae) larval developmental habitat at round hay bale feeding sites. J. Med. Entomol 46: 1310–1319.

Taylor, D. B., and D. Berkebile. 2006. Comparative efficiency of six stable fly (Diptera: Muscidae) traps. J. Econ. Entomol 99: 1415–1419.

Taylor, D. B., and D. R. Berkebile. 2011. Phenology of stable fly (Diptera: Muscidae) larvae in round bale hay feeding sites in eastern Nebraska. Environ. Entomol 40: 184–193.

Taylor, D. B., D. R. Berkebile, and P. J. Scholl. 2007. Stable fly population dynamics in eastern Nebraska in relation to climatic variables. J. Med. Entomol 44: 765–771.

Taylor, D. B., K. Friesen, J. J. Zhu, and K. Sievert. 2012. Efficacy of cyromazine to control immature stable flies (Diptera: Muscidae) developing in winter hay feeding sites. J. Econ. Entomol 105: 726–731.

Taylor, D. B., R. D. Moon, and D. R. Mark. 2012. Economic impact of stable flies (Diptera: Muscidae) on dairy and beef cattle production. J. Med. Entomol 49: 198–209.

Taylor, D. B., K. Friesen, and J. J. Zhu 2013. Spatial-temporal dynamics of stable fly (Diptera: Muscidae) trap catches in eastern Nebraska. Environ. Entomol 42: 524–531.

Taylor, D., K. Friesen, and J. Zhu. 2014. Stable fly control in cattle winter feeding sites with Novaluron. Arthropod Manag. Tests 39: 1–2.

Taylor, D. B., K. Friesen, and J. Zhu. 2017. Precipitation and temperature effects on stable fly (Diptera: Muscidae) population dynamics. Environ. Entomol 46: 434–439.

Taylor, D. B., K. Harrison, and J. J. Zhu. 2020. Methods for surveying stable fly populations. J. Insect Sci 20:17, 1–8.

Teskey, H. 1969. On the behavior and ecology of the face fly, *Musca autumnalis* (Diptera: Muscidae). Can. Entomol 101: 561–576.

Thimijan, R. W., L. G. Pickens, and N. O. Morgan. 1973. Responses of the house fly stable fly and face fly to electromagnetic radiant energy. J. Econ. Entomol 66: 1269–1270.

Thomas, G. D., and C. E. Morgan. 1972. Field-mortality studies of the immature stages of the horn fly in Missouri. Environ. Entomol 1: 453–459.

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022

Thomas, G. D., and C. W. Wingo. 1968. Parasites of the face fly and two other species of dung-inhabiting flies in Missouri. J. Econ. Entomol 61: 147–152.

Thomas, G. D., B. Puttler, and C. E. Morgan. 1972. Further studies of field parasitism of the face fly by the nematode *Heterotylenchus autumnalis* in central Missouri, with notes on the gonadotrophic cycles of the face fly. Environ. Entomol 1: 759–763.

Thomas, G. D., R. D. Hall, C. W. Wingo, D. B. Smith, and C. E. Morgan. 1983. Field mortality studies of the immature stages of the face fly (Diptera: Muscidae) in Missouri. Environ. Entomol 12: 823–830.

Thomas, G. D., I. L. Berry, D. R. Berkebile, and S. R. Skoda. 1989. Comparison of three sampling methods for estimating adult stable fly (Diptera: Muscidae) populations. Environ. Entomol 18: 513–520.

Thomas, G. D., S. R. Skoda, D. R. Berkebile, and J. B. Campbell. 1996. Scheduled sanitation to reduce stable fly (Diptera: Muscidae) populations in beef cattle feedlots. J. Econ. Entomol 89: 411–414.

Thompson, H. M. 1999. Esterases as markers of exposure to organophosphates and carbamates. Ecotoxicology 8: 369–384.

Thrift, F. A., and J. R. Overfield. 1974. Impact of pinkeye (Infectious Bovine Kerato-Conjunctivitis) on weaning and postweaning performance of Hereford calves. J. Anim. Sci 38: 1179–1184.

Todd, D. H. 1964. The biting fly *Stomoxys calcitrans* (L.) in dairy herds in New Zealand. N. Z. J. Agric. Res 7: 60–79.

Tomberlin, J. K., T. L. Crippen, A. M. Tarone, M. F. B. Chaudhury, B. Singh, J. A. Cammack, and R. P. Meisel. 2017. A review of bacterial interactions with blow flies (Diptera: Calliphoirdae) of medical, veterinary, and forensic importance. Ann. Entomol. Soc. Am 111: 19–36.

Trout Fryxell, R. T., R. Moon, D. Boxler, and D. Watson. 2021. Face fly (Diptera: Muscidae)—biology, pest status, current management prospects, and research needs. J. Integr. Pest Manag 12: 5.

Tugwell, P., E. C. Burns, and J. W. Turner. 1969. Brahman breeding as a factor affecting the attractiveness or repellency of cattle to the horn fly. J. Econ. Entomol 62: 56–57.

Turner, E. C., Jr., R. P. Burton, and R. R. Gerhardt. 1968. Natural parasitism of dung-breeding Diptera: a comparison between native hosts and an introduced host, the face fly. J. Econ. Entomol 61: 1012–1015.

Untalan, P. M., J. H. Pruett, H. N. Atteberry, and C. D. Steelman. 2006. Thrombostasin isoform frequency in a Central Texas field population of the horn fly, *Haematobia irritans*. Vet. Parasitol 142: 359–366.

U.S. Department of Agriculture, National Agricultural Statistics Service. 2007. Census of agriculture. https://www.nass.usda.gov/Publications/AgCensus/2007/index.php.

U.S. Department of Agriculture, National Agricultural Statistics Service. 2017. 2017 Census of agriculture. https://www.nass.usda.gov/Publications/AgCensus/2017/index.php.

U.S. Department of Agriculture, Economic Research Service. 2020. Commodity costs and returns. https://www.ers.usda.gov/data-products/commodity-costs-and-returns/commodity-costs-and-returns/#Historical%20Costs%20and%20Returns:%20Cow-Calf.

U.S. Department of Agriculture National Animal Health Monitoring System. 2011. Feedlot 2011 part IV: health and health management on US feedlots with a capacity of 1,000 or more head (no. 638.0913). USDA–APHIS–VS–CEAH–NAHMS, Fort Collins, CO.

U.S. Environmental Protection Agency. 2021. Inventory of U.S. greenhouse gas emissions and sinks. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

Valiela, I. 1969. An experimental study of the mortality factors of larval *Musca autumnalis* DeGeer. Ecol. Monogr 39: 199–225.

Vijverberg, H. P., J. M. van der Zalm, and J. van den Bercken. 1982. Similar mode of action of pyrethroids and DDT on sodium channel gating in myelinated nerves. Nature 295: 601–603.

Vitela-Mendoza, I., C. Cruz-Vázquez, J. Solano-Vergara, and A. Orihuela-Trujillo. 2016. Short communication: relationship between serum cortisol concentration and defensive behavioral responses of dairy cows exposed to natural infestation by stable fly, *Stomoxys calcitrans*. J. Dairy Sci 99: 9912–9916.

Ward, J. K., and M. K. Nielson. 1979. Pinkeye (Bovine Infectious Keratoconjunctivitis) in beef cattle. J. Anim. Sci 49: 361–366.

Warnes, M. L., and L. H. Finlayson. 1987. Effect of host behaviour on host preference in *Stomoxys calcitrans*. Med. Vet. Entomol 1: 53–57.

Watts, K. J., and R. L. Combs Jr. 1977. Parasites of *Haematobia irritans* and other flies breeding in bovine feces in northeast Mississippi. Environ. Entomol 6: 823–826.

Weeks, E. N. I., 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.

Whisnant, C. S., T. E. Kiser, and F. N. Thompson. 1985. Effect of calf removal on serum luteinizing hormone and cortisol concentrations in postpartum beef cows. Theriogenology 24: 119–129.

Whittle, A. J., S. Lenhart, L. J. Gross, A. J. Whittle, S. Lenhart, and L. J. Gross. 2007. Optimal control for management of an invasive plant species. Math. Biosci. Eng 4: 101–112.

Wieman, G. A., J. B. Campbell, J. A. Deshazer, and I. L. Berry. 1992. Effects of stable flies (Diptera: Muscidae) and heat stress on weight gain and feed efficiency of feeder cattle. J. Econ. Entomol 85: 1835–1842.

Wienhold, B. J., and D. B. Taylor. 2012. Substrate properties of stable fly (Diptera: Muscidae) developmental sites associated with round bale hay feeding sites in Eastern Nebraska. Environ. Entomol 41: 213–221.

Williams, D. F. 1973. Sticky traps for sampling populations of *Stomoxys calcitrans*. J. Econ. Entomol 66: 1279–1280.

Williams, R. E. 2009. Veterinary entomology: livestock and companion animals. CRC Press, Boca Raton, FL.

Williams, R. E., and E. J. Westby. 1980. Evaluation of pyrethroids 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, 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. Entomol 105: 257–261.

Zacks, D., and E. Loew. 1989. Why is alsynite fiber glass sheet attractive to stable flies? Optical and behavioural studies. Exp. Biol 48: 215–222.

Zhu, J., X. Zeng, D. Berkebile, H. Du, Y. Tong, and K. Qian. 2009. Efficacy and safety of catnip (*Nepeta cataria*) as a novel filth fly repellent. Med. Vet. Entomol 23: 209–216.

Zhu, J. J., C. A. Dunlap, R. W. Behle, D. R. Berkebile, and B. Wienhold. 2010. Repellency of a wax-based catnip-oil formulation against stable flies. J. Agric. Food Chem 58: 12320–12326.

Zhu, J. J., A. Y. Li, S. Pritchard, K. Tangtrakulwanich, F. P. Baxendale, and G. Brewer. 2011. Contact and fumigant toxicity of a botanical-based feeding deterrent of the stable fly, *Stomoxys calcitrans* (Diptera: Muscidae). J. Agric. Food Chem 59: 10394–10400.

Zhu, J., D. R. Berkebile, C. Dunlap, A. Zhang, D. Boxler, K. Tangtrakulwanich, R. Behle, F. Baxendale, and G. Brewer. 2012. Nepetalactones from essential oil of *Nepeta cataria* represent a stable fly feeding and oviposition repellent. Med. Vet. Entomol 26: 131–138.

Zhu, J., B. Wienhold, J. Wehrle, D. Davis, H. Chen, D. Taylor, K. Friesen, and L. Zurek. 2014. Efficacy and longevity of newly developed catnip oil microcapsules against stable fly oviposition and larval growth. Med. Vet. Entomol 28: 222–227.

Zhu, J. J., G. J. Brewer, D. J. Boxler, K. Friesen, and D. B. Taylor. 2015. Comparisons of antifeedancy and spatial repellency of three natural product repellents against horn flies, *Haematobia irritans* (Diptera: Muscidae). Pest Manag. Sci 71: 1553–1560.

Zhu, J. J., Q. Zhang, D. B. Taylor, and K. A. Friesen. 2016. Visual and olfactory enhancement of stable fly trapping. Pest Manag. Sci 72: 1765–1771.

Zhu, J. J., S. C. Cermak, J. A. Kenar, G. Brewer, K. F. Haynes, D. Boxler, P. D. Baker, D. Wang, C. Wang, A. Y. Li, *et al.* 2018. Better than DEET repellent compounds derived from coconut oil. Sci. Rep 8: 14053.

Zimmermann, G. 2008. The entomopathogenic fungi *Isaria farinosa* (formerly *Paecilomyces farinosus*) and the *Isaria fumosorosea* species complex (formerly *Paecilomyces fumosoroseus*): biology, ecology and use in biological control. Biocontrol Sci. Technol 18: 865–901.

Downloaded from https://academic.oup.com/jipm/article/13/1/14/6578699 by University of Tennessee Libraries user on 13 May 2022