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

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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 (McCherney 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...
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.

Fifth 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 fifth 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 (Oyzzzin et al. 2008).

The purpose of this manuscript is to evaluate the economic impact and management of three 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
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 (Machtlinger 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 the 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, Kraus 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$389.9 million, and US$33.2 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. 1992); 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...
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 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
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 operation) 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. Catanguí 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, Martinez 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...
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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:

\[
TFC_1 = \sum_{i=1}^{n} c_{HF} + c_{FF} + c_{SF}^i,
\]

where \( TFC \) represents the total fly costs (\$/time period, \( t \), obtained by summing over the animals with index \( i \) (\( i = 1, \ldots, n \)), \( c_{HF} \) 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 except 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). 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).
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...
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 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.

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