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Review Article

Management Strategies for Reducing the Risk of Equines Contracting Vesicular Stomatitis Virus (VSV) in the Western United States

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A B S T R A C T

Vesicular stomatitis viruses (VSVs) cause a condition known as vesicular stomatitis (VS), which results in painful lesions in equines, cattle, swine, and camelids, and when transmitted to humans, can cause flu-like symptoms. When animal premises are affected by VS, they are subject to a quarantine. The equine industry more broadly may incur economic losses due to interruptions of animal trade and transportation to shows, competitions, and other events. Equine owners, barn managers, and veterinarians can take proactive measures to reduce the risk of equines contracting VS. To identify appropriate risk management strategies, it helps to understand which biting insects are capable of transmitting the virus to animals, and to identify these insect vectors' preferred habitats and behaviors. We make this area of science more accessible to equine owners, barn managers, and veterinarians, by (1) translating the most relevant scientific information about biting insect vectors of VSV and (2) identifying practical management strategies that might reduce the risk of equines contracting VSV from infectious biting insects or from other equines already infected with VSV. We address transmission risk at four different spatial scales—the animal, the barn/shelter, the barnyard/premises, and the surrounding environment/neighborhood—noting that a multiscale and spatially collaborative strategy may be needed to reduce the risk of VS.

1. Vesicular Stomatitis: What, Where, and Why Care?

Vesicular stomatitis (VS) is a disease that can affect equines and a variety of other livestock species, such as cattle, swine, and camelids. It is caused by viruses from the genus *Vesiculovirus* within the family Rhabdoviridae [1]. Two viruses, *Vesiculovirus* New Jersey and *Vesiculovirus* Indiana, are the main causes of VS in the United States [2]. Vesicular stomatitis virus (VSV) spreads primarily from infected to susceptible animals through biting insects [1]. However, it can also spread through direct contact with virus-containing fluids from infectious lesions and saliva or through indirect contact with contaminated fomites, such as shared water, feed, feeders, lick tubs, tack, and veterinary supplies such as drenching equipment [3,4].

Clinical signs of VS in equines include excessive salivation followed often by blisters and lesions located on the nostrils, muzzle, lips, oral mucosa, tongue, teats, sheath, ears, or coronary bands of the hooves [4,5]. See Fig. 1 for example photographs, as well as the study by Timoney 2016 [5] and Green 1993 [6]. Animals usually recover within a few weeks, unless secondary bacterial infections, laminitis, or other complications occur [7]. Most concerning for the livestock industry is that these signs of VS in cattle and swine are

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visually indistinguishable from foot-and-mouth disease [3], which has been eradicated from the United States since 1929 [8]. Fortunately, equines are not susceptible to foot-and-mouth disease, so they serve as useful sentinels to help distinguish between these two look-alike diseases [3].

For public safety, it is important to be aware that humans can also contract VSV from infected animals, particularly through droplets such as when an infected animal sneezes in the face of a handler or when saliva from an infected animal enters the handler's eyes, nose, mouth, or wounds on their hands or arms [9]. In humans, symptoms include fever, headache, muscle pain, and chills for three to five days; only in a minority of human cases do blister-like lesions appear on the lips, tongue, oral cavity, throat cavity, or nose [9–11]. More severe symptoms such as nausea and vomiting have been documented [12], and in extremely rare cases, encephalitis has occurred in children [13].

Vesicular stomatitis occurs seasonally every year in southern Mexico, Central America, and northern South America. It emerges from these tropical areas sporadically, causing intermittent incursions of VS into the western United States (every several years to decades), primarily in Texas, New Mexico, and Arizona, with subsequent years of geographic expansion northward involving many other states, including Colorado, Utah, Wyoming, Kansas, Nebraska, South Dakota, Montana, and Idaho [2,14–18]. When one or more equines at a premises become infected, the virus can spread quickly to susceptible animals [19,20]. Therefore, a premises with one or more infected equines is subject to quarantine, in which animal movements are temporarily halted not just to and from the affected premises, but also potentially between counties, states, and nations [15,21,22]. These movement bans may cause notable economic losses [23]. In addition, owners of quarantined premises incur economic costs associated with reactive mitigation strategies and biosecurity efforts, such as isolating infected animals; withdrawing them from events, shows, competitions, or on-site use; turning away new boarders (at commercial barns); engaging a veterinarian; purchasing animal health supplies, cleaning feeders, watering tanks, and tack; as well as controlling insects [24–26]. Premises with confirmed cases are placed under quarantine until 14 days after lesions appear on the last affected animal at that premises [27].

Quarantined premises are often located within close proximity (<1 km) to standing water (e.g., ponds, wetlands, puddles, livestock water tank overflow) or to streams, irrigation ditches, and other moving water [28]. This predisposed position within the landscape—when combined with knowledge of relationships across space or through time among vegetation, precipitation, and insect habitat and dispersal conditions [29]—provides opportunities for equine owners to implement proactive risk management strategies to reduce the probability of VS affecting their individual premises. Here, we describe the three most common insect vectors of VSV, and then discuss practical vector mitigation and animal husbandry strategies—ranging in scale from an individual animal to the local neighborhood—which might reduce the risk or effects of VS on equids, their owners, neighboring premises, and the equine industry. These proactive risk reduction efforts are increasingly important in light of expanding ranges of insect vectors [30], heightened awareness of animal health and welfare, and robust interstate and international horse trade [31,32].

2. Vesicular Stomatitis Virus Transmission by Biting Flies

Insects play a critical role in disseminating VSV between herds and across long distances during outbreaks [4,19]. Likely vectors of VSV include a wide range of blood-feeding or tissue-feeding flies, most notably sand flies (Psychodidae), *Culicoides* biting midges (Ceratopogonidae), and black flies (Simuliidae) (Fig. 2). Species from all three of these families have been found naturally infected with VSV in the wild [15,33,34]. Some additional insect species have been infected under laboratory conditions and may play a role in transmission not yet understood, such as mosquitoes (Culicidae), eye gnats (Chloropidae), face flies and house flies (Muscidae), grasshoppers (Acrididae), along with a myriad of other insects [35–38].

The primary blood-feeding flies implicated in VSV transmission lay eggs, develop, and emerge from distinctive habitats. Sand flies (*Lutzomyia* spp.) prefer high-nutrient areas that remain dry throughout the years, such as tree holes, rock crevices, and animal burrows [39]. Biting midges (*Culicoides* spp.) prefer high-nutrient areas that remain wet or very moist, such as wet leaves, mulch, compost, leaf litter, waterlogged soils with animal feces, and mud around ponds and troughs [40]. Black flies (*Simulium* spp.) prefer aquatic habitats that have flowing water, such as irrigation ditches, lake outflows, springs, rivers, or streams [41,42].

Adult flies are not confined to the vicinity of their immature larval habitats. The adults disperse outward through active flight and passive windborne flight. Sand flies are weak fliers and tend to disperse small distances, from less than 100 meters up to 1.5 km [43]. Biting midges can fly up to 4 km from the breeding source over

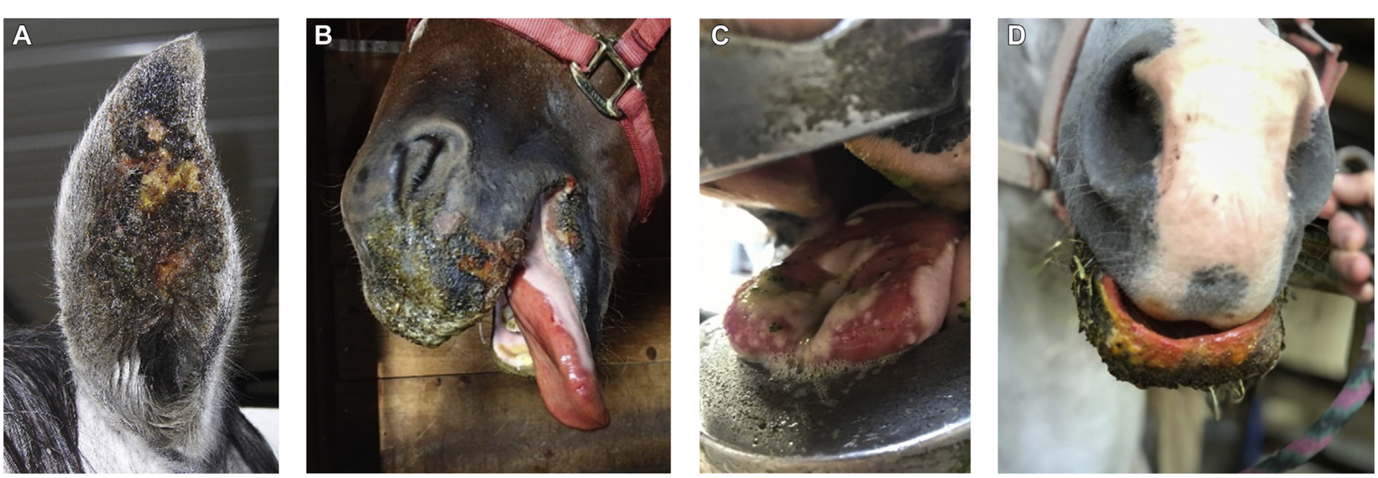

Fig. 1. Clinical signs of vesicular stomatitis (VS) in infected horses: (A) lesions in the ear [photo by Richanne Lomkin]; (B) lesions on the tongue, lips, and nostril [photo by Jason Lombard]; (C) lesions on the tongue [photo by Randy Lewis]; (D) lesions on the lower lip [photo by Piper Norton].

the course of multiple nights and be carried by the wind hundreds of kilometers [44,45]. Black flies are the best dispersers among the probable vectors [41]. Some species are capable of traveling more than 12 km per day from their larval sites, although an average of 3 km per day is more likely [46–48]. Adult black flies live an average of 14–21 days [49], yet have been documented to live up to 85 days [50]. They can also be carried by the wind for hundreds of kilometers [45]. The dispersal ability of these flies means that sources of potential vectors are not necessarily onsite and may originate from surrounding areas.

It is difficult to identify a precise “vector season” because the full suite of insect vectors of VSV is not definitively known. That said, outbreaks typically begin during spring in the southwestern United States (e.g., Texas, New Mexico, and Arizona), progress northward into the Rocky Mountain and central Plains regions (e.g., Colorado, Wyoming, Nebraska, Utah, Idaho, and Montana) as temperatures warm, and taper off with freezing nighttime temperatures (see [51,52] for timelines from past outbreaks; see the study by Peters et al. [18] for the relationship between week of VS onset, latitude, and long-term rainfall). This is consistent with the seasonal activity of adult sand flies, biting midges, and black flies, which is confined mainly to warmer months of the year.

These insect-vectors vary widely in the time of year they emerge, how early or late into the cold season they can persist, whether adults in addition to larvae are capable of overwintering, and thus how many generations might emerge within a single year (see [53] for an example). Some black fly species emerge all at once (i.e., univoltine) in spring and early summer (as early as January in southern regions and as late as June in more northern regions), rarely being found in traps after July. Other black fly species do not emerge all at once (i.e., multivoltine), first appearing in spring and increasing in abundance during each generation until the first killing frost [54].

Black fly species tend to lay their eggs in running water with stable substrate (e.g., rivers, streams, irrigation ditches). These eggs develop the following spring into larvae, which attach themselves to rocks, aquatic vegetation, or woody debris and filter-feed on suspended particulate matter [55]. These larvae eventually emerge as adults when food quantity and quality are adequate, and when water temperatures have been sufficiently high to accumulate enough developmental day-degrees above 0°C (i.e., D°C) [55]. Degree-day requirements range widely across species; for example, from 240 to 525 D°C among different black fly species occupying the same stretch of a stream at the same time [56]. Therefore, once the cold season arrives, black flies are unlikely to emerge in response to an itinerate warm-spell. Water temperatures are unlikely to remain at effective temperatures long enough to trigger larval development into emergent adults [41,57].

Sand flies are thought to shelter (i.e., estivate) in rock crevices or rodent burrows during cold temperatures. They become active only during specific weeks or months of the year, which vary by region. But even in climates with more consistently warm temperatures year-round, they are still highly seasonal [39]. This seasonal fidelity makes it relatively more straightforward to identify a “vector season” for sand flies than for black flies.

Biting midges typically emerge in spring (though not all at once), decline throughout the summer, and resurge in the fall [58–61]. As multivoltine species, up to six generations can be produced within a single year [59], until temperatures become too cold. *Culicoides* are typically thought to survive no longer than 10–20 days at below-freezing temperatures (0°C), yet up to three months at 10°C [62–64]. Eggs are the most cold-hardy life-stage for *Culicoides*, tolerating brief exposure to temperatures as low as -20°C. By contrast, larvae are the least cold-hardy stage. Although they can overwinter successfully in the presence of snow and ice [53], they do suffer complete mortality at < -4°C [65].

Even if a frost event has occurred after an outbreak, susceptible livestock that have been moved out of a high-risk area should not be brought back to the area until quarantines have been lifted, or if no quarantines are in place, until no symptomatic animals remain. This is because susceptible animals can still contract VSV from infected animals, either through direct contact with fluids from their lesions, or indirectly through shared water, feed, buckets, tack, and veterinary equipment, or possibly through continued activity of infected biting insects that are more cold-hearty or find refuge from the cold.

In addition to differences in their seasonality of emergence, biting insects also vary in their active feeding times within a 24-hour (diel) period [60]. Sand flies are primarily nocturnal, although some species (e.g., *Lutzomyia diabolica*) attack during the day (i.e., are diurnal) [39,66,67]. Biting midges tend to be crepuscular, with peak flight activity and feeding typically occurring 2 hours before and after sunset and again around sunrise. However, some biting midge species are nocturnal and others diurnal [60,68,69]. Black flies tend to be active during the day and early evening, rarely biting at night [41,57]. This temporal diversity among biting insects makes it difficult for a single management strategy to effectively reduce the risk of equines contracting VSV. An assessment of the potential vector (or multiple vectors) within proximity of an equine premises is needed to determine at which time(s) of day animals are most at risk of being attacked (Tables 1 and 2).

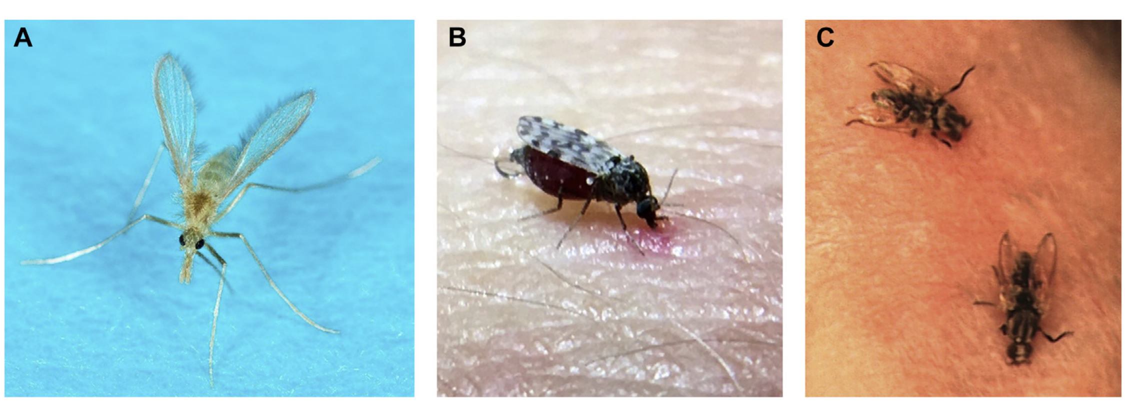

Fig. 2. (A) Sand fly, *Phlebotomus papatasi* [photo by Stephen Ausmus]; (B) Biting midge, *Culicoides sonorensis*, one-sixteenth-inch (<2 mm) long [photo by Paula Rozo Lopez]; (C) Black fly, Simuliidae [photo by Daniel Mead].

3. Reducing VS Risk Through Insect-Vector Management

Risk of insect-transmitted VS in horses can be reduced through a combination of proactive, protective measures, and environmental controls [70]. Protective measures include moving equines away from insect-vector habitats, such as near rivers, streams, irrigation canals, wetlands, ponds, or other standing bodies of water; keeping them in shelters during high-risk periods; and applying chemical repellents to susceptible animals. Environmental controls include enhanced levels of sanitation around the premises, mechanical barriers (e.g., mesh sheets, or screens on barn openings), and using propane-fueled insect traps placed strategically at local or neighborhood scales.

When an insect vector emerges from a river, wetland, or rocky area in a neighborhood with equine premises, these vectors may fly or be carried on the wind toward the premises, into paddocks and barns, eventually alighting on susceptible equines. Next, we discuss proactive ways to interrupt this vector and reduce risk at four spatial scales, which we present in the order of the vector's path, from beyond to within a premises: 1) the neighborhood scale (i.e., local area or region, including grasslands and improved pastures where equines might be turned out for grazing), 2) the premises scale (i.e., barnyard, paddock, corral), 3) the shelter scale (i.e., barn, stable, loafing shed), and 4) the individual animal scale.

3.1. Neighborhood

Good management strategies include keeping animals away from areas where biting insects are likely to be concentrated during relevant times of the year: near rivers, streams, and irrigation canals, where black fly adults emerge; near ponds, mudflats, wetlands, damp forests, and other high-moisture habitats, which biting midges prefer; or near dry rock crevices, caves, or animal burrows, where mammal-feeding sand flies reside.

Unfortunately, exclusion of animals from areas with high insect activity (e.g., near rivers, streams, irrigation canals, or wetlands during relevant periods [18]) might require a manager to provide them with alternative water sources, which could be logistically and financially challenging. An alternative approach is to time the rotation of animals through pastures to avoid grazing them near a stream that is just returning to its base flow after reaching peak runoff—a condition which has been correlated with past outbreaks [28]. Similarly, moving animals to higher-elevation pastures (>1,200 m or 4,000 ft) during the height of vector season could help avoid attack, especially from biting midges [71].

Unfortunately, biting midges and black flies can travel several kilometers per day from their larval development sites [41,44], so there are no guarantees that the avoided insects are the only relevant vectors in the area. One could imagine, for example, moving horses away from a stream with muddy banks to avoid biting midges only to encounter black flies near a flowing irrigation canal, or sand flies in a dry pasture with rock crevices.

Pesticide applications to insect habitats in the neighborhood or region might be a tempting management option. However, this approach is limited in its potential because few pesticides are labeled for safely controlling insect vectors in rivers and wetlands [40,44,72]. Furthermore, vectors can migrate away from their larval development sites and shelter in untreated areas. Lillie et al. [44] conclude for biting midges in northeastern Colorado that—given their ability to travel at least 2.8 km in a single night and as much as 4 km in two nights—you would need to treat 3.57 km^2 (865 acres) around a single larval habitat site to manage biting midges. And this naively assumes that a treated site is the only suitable larval habitat in the area [73]. To be effective, local control efforts need specific knowledge of the relevant insect vectors and all larval sites in an area, which is challenging. Larger-scale management efforts face additional safety, health, logistical, economic, and legal challenges. For example, pesticide labels and environmental laws might prevent pesticide applications to drinking water sources, rivers, wetlands, or anywhere near pollinator habitat, bee hives, and organic farms.

An alternative option that faces fewer safety and legal restrictions and lower economic thresholds is propane-fueled insect traps, which attract biting insects by emitting CO_2. Covering roughly four acres per device, these traps would need to be placed between a known breeding/larval habitat (e.g., a mud flat) and premises at risk of invasion [74,75]. Currently, these devices cost (in 2018 dollars) roughly $700 each and $24 to refill the propone tank every 14 days. One important limitation is that they are not effective in windy conditions, when the CO_2 plume becomes too diluted to attract insects. Fortunately, most biting flies are relatively inactive under windy conditions [45].

The scale at which propane-fueled insect traps function—every four acres between vector habitat and susceptible premises—may require coordination among neighbors to be effective. Suppose, for

Table 1
Primary insect vectors suspected in VSV transmission and their geographic distribution, preferred habitats, and time of day when they typically feed on mammals, such as equines.

Common Name	Sand Flies	Biting Midges	Black Flies
Scientific Name	*Lutzomyia* spp.	*Culicoides* spp.	*Simulium* spp.
Geographic Distribution	Mammal-feeding species are currently known to exist in Texas, New Mexico, Arizona, Nevada, Utah, Colorado, and Kansas	Found across North America	Found across much of North America
Preferred Habitats	Dry conditions, such as those found in rock crevices, animal burrows, and tree cavities.	Muddy and wet conditions, such as around water troughs, ponds, and wetlands. Areas of high organic waste, such as puddles at the base of manure piles.	Running water with stable substrate, such as streams or irrigation canals with rocks, aquatic vegetation, or woody debris. They also like larger, slower, and meandering rivers.
Ability to Disperse Actively by Flight	Weak: <100 m to 1.5 km. No evidence of long-distance dispersal by wind.	Moderate: on average, 1.89 km over 8 nights, but up to 4 km in total from their breeding habitat. Wind may carry them hundreds of kilometers.	Strong: up to 12 km per day, with average adult life spans of 14–21 days. Wind may carry them hundreds of kilometers.
Active Time(s) of Day	Mostly nocturnal feeding. However, some species feed in the daytime (diurnal).	Mostly crepuscular: feeding 2 hours before and after sunset and again around sunrise. However, some species are nocturnal or diurnal.	Mostly crepuscular: feeding during the early evening. However, some daytime (diurnal) feeding occurs. Rarely bite at night.
Reference to Learn More	[39]	[40]	[41]

Abbreviation: VSV, vesicular stomatitis virus.

Table 2
Time of day to expect various VSV vectors, or combinations of vectors, to be active and possibly feeding on equines.

Insect Vector in Your Area *(and its preferred habitat†)*	**Night-time**	**Around Sunrise**	**Day-time**	**Around Sunset**
(a) Sand flies *(prefer dry rock crevices or burrows)*	Dark red	Light green	Yellow	Light green
(b) Biting midges *(prefer mud or wet organic waste)*	Yellow	Dark red	Yellow	Dark red
(c) Black flies *(prefer flowing water)*	Light green	Dark red	Yellow	Dark red
If Multiple Insect Vectors are in Your Area‡				
(a) & (b) Sand flies & Biting midges	Dark red	Dark red	Yellow	Dark red
(a) & (c) Sand flies & Black flies	Dark red	Dark red	Yellow	Dark red
(b) & (c) Biting midges & Black flies	Yellow	Dark red	Yellow	Dark red
(a) & (b) & (c) Sand flies & Biting midges & Black flies	Dark red	Dark red	Yellow	Dark red

† Insect vectors' preferred habitats are summarized in parentheses to help identify which vectors are most likely in a neighborhood based on proximity to that habitat.

‡ When multiple vectors occur in your neighborhood, it becomes harder to find a time of day when equines are not at risk of being bitten by one or more of these vectors.

Dark red indicates times of day a vector is most typically active. Yellow indicates other times of day the vector is known to be active, though less typical. Light green indicates times of day the vector is not typically active.

example, that a susceptible premises does not own or manage the optimal locations for insect trap placement and maintenance. In cases where multiple landowners are involved, a homeowners' association, subdivision board, or conservation district could potentially help facilitate collaboration across a neighborhood. Experts on VSV could lead informational meetings for these organizations and potentially provide grants or matching funds to help cover costs associated with deploying management strategies in a coordinated manner across multiple landowners.

3.2. Premises

Good barnyard management practices, such as removing manure regularly from a premises to reduce larval habitat for biting midges, will help reduce insect populations. Biting midges are especially attracted to wet organic matter, such as manure-enriched mud [76,77]. Therefore, it is not sufficient to simply cover manure piles to discourage insects from landing directly on them [78].

Another good barnyard management practice is to maintain sloped and well-drained sand and porous gravel around water troughs and other water sources to help reduce populations of biting insects. At least one VSV vector (a biting-midge species) has been associated with mud around water troughs [79]. However, other species of biting midge are not, indicating that a variety of management practices are needed to manage biting midges. This is to say, a single management practice is not sufficient to protect equines from the variety of insect species that may transmit VSV to them. For example, any small-scale, low-lying areas around the premises where water tends to pool (e.g., potholes in driveways or depressions in paddocks) should also be filled with sand or gravel to improve drainage and reduce habitat for biting midges.

Vegetation management is often used as a strategy to help reduce insect pressure on premises, although the effects on VSV transmission are less direct. Shorter vegetation mostly affects biting midges and black flies—which are known to harbor in standing vegetation—as do mosquitoes and ticks, which carry other animal pathogens of concern. In addition, aphids live on standing vegetation and attract black flies and mosquitoes, which feed on the partially digested sap and sugars that aphids excrete [80–82]. This sugar byproduct actually lengthens the life span of midges, which increases their likelihood of incubating VSV long enough to become infectious [82].

Standing vegetation is primarily a risk because it provides habitat for biting insects. However, it could also facilitate the spread of VS from an infected equine to other colocated equines if the vegetation becomes contaminated by saliva from the infected equine's tongue and gum ulcers, or fluids from their muzzle lesions. Vesicular stomatitis viruses can survive on the surfaces of plant species for up to 24 hours [38]. A susceptible horse might be exposed to this virus source by grazing the same area, contracting it orally.

A related way that vegetation can play a role in VS transmission is through grasshoppers, which are often found in standing vegetation and baled hay. Grasshoppers can become infected by foraging on plants contaminated with VSV and then transmit it to animals that accidentally ingest them [37,38]. This may sound unlikely, but transmission has been documented in cattle that ingested VSV-infected grasshoppers while grazing [37].

Thoughtful sanitation practices and vegetation management around a premises, including careful management of irrigation to minimize pooled water and mud in pastures and fields, could reduce the risk of some, but not all, VSV transmission pathways [1]. This final example highlights another case in which coordination among multiple land owners within the same neighborhood might be necessary. A premises with susceptible equines might not own/manage a nearby irrigated meadow or field that provides vector habitat. In this case, regardless of their efforts to properly deploy vector management strategies on their own property, their success at reducing VSV risk might hinge on the willingness of neighbors to cooperate.

3.3. Shelter

Moving equine animals indoors can also reduce their exposure to some insect vectors [70]. Black flies, for example, are known to avoid entering buildings or structures with a roof and three or more walls [16,41,83,84]. Thus, moving equines into a barn or other indoor or partially indoor structure during the day, or simply allowing horses access to a run-in shed within the pasture, when black flies tend to feed (Table 2; [57]), can potentially reduce transmission risk [20,70,85]. For equines exposed to biting midges and sand flies, which feed during low light conditions (crepuscular or nocturnal), shelter would be needed from dusk through dawn (Table 2; [39,68]). For equines exposed to a combination of black flies and either biting midges or sand flies, this management strategy can be problematic—requiring sheltering 24 hours a day to reduce the risk of attack. Attention should therefore be paid to which vectors are active in an area and at what times (Table 2), adjusting the sheltering schedule accordingly.

Total exclusion of biting insects from shelters or barns is impractical, both logistically and economically. Furthermore, barrier treatments such as pyrethroids sprayed on buildings or surrounding vegetation have rarely produced meaningful control results when tested in the field [86–88]. But one notable exception occurred in Queensland, Australia, where Standfast et al. [89] significantly reduced the adult biting midge population by applying a 0.1% bifenthrin-in-water mix to external resting surfaces (i.e., fences, walls, and ornamental vegetation). This barrier treatment, however, has not been tested and approved in the United States.

In the absence of legal and effective barrier treatments, equine owners need alternative shelter-level strategies. Keeping barn doors and windows closed during hours that vectors are active can reduce their abundance inside [90], although its effectiveness can be inconsistent [91]. To further reduce biting insect pressure inside shelters, densely meshed nets (pore-size of 0.1825 mm^2) or repellent-treated fabric can be installed on windows and doors, around stalls, or as an outdoor net-shed [90–95]. Barn managers should also minimize the use of bright lights, including insect light traps or zappers, which can accidentally draw insects into shelters at night from the barnyard or potentially infected neighboring premises [96].

The use of fans in barns to increase air circulation in general, or that blow directly down on horses, is inconsistent at deterring feeding insects, being effective in some situations but detrimental in others [90,91,97]. Fans (six-bladed, 1,300 mm by 1,380 mm in size, with power consumption of 0.75 kW, and wind speeds of 10–15 km/hour) blowing into an outdoor paddock where equines have access to a tent-shelter or net-shed can reduce biting midges from landing on animals long enough to feed [91].

3.4. Individual Animal

Topical insecticides and repellents might reduce an individual equine's exposure to biting insects [91,98,99]. However, they are not equally effective against all species, with some biting flies being less affected than others by active ingredients [100,101]. Studies specifically on repellents against biting midges, black flies, and sand flies typically show they are either ineffective or only effective for a few hours or days [102–105]. Vesicular stomatitis outbreaks can last several weeks to months, so repellants should be used in combination with other complementary and longer-term management strategies (e.g., removing manure, constructing run-in sheds, etc.) [106].

Another common protective measure is to place cloth barriers on individual animals (e.g., fly sheets, leg wraps, fly masks, and ear nets) [99,107,108]. These barriers are more effective when the mesh size is small enough (e.g., biting midges are less than 1 mm wide [109]) and when they are treated with synthetic pyrethroids (e.g., deltamethrin, pyrethrin, permethrin) [93,101,110–112]. That said, pyrethroids are contact-toxicants and not spatial repellants [113], so they only protect areas of the skin located directly under treated fabric. They do not protect adjacent areas of skin that remain exposed (e.g., a horse's unprotected muzzle, ears, or coronary bands).

Beyond the usual areas of the body that biting insects favor—such as the belly, legs, flanks, hindquarters, and ears [114]—abrasions also provide good points of entry for the virus [85]. So equines with wounds, or those that are nursing offspring and might therefore have teat or udder abrasions [115], should have extra care taken to reduce exposure to insect vectors.

If an equine becomes infected with VSV and develops VS, lesions will form only at the site where the bite or exposure occurred [116]. For example, a horse wearing a permethrin-treated fly mask can be bitten by an insect vector on its exposed muzzle with lesions developing here. Vesicular stomatitis virus can then be spread to other equines at the premises through shared water troughs, feed buckets, etc. Furthermore, susceptible insects that feed at an animal lesion site can contract VSV—either directly from an infected animal or from cofeeding with already infected insects on an uninfected equine [117]—and then transmit it to future blood meal victims [116].

4. Discussion and Conclusions

With an understanding of the habitats and behaviors of the primary VSV insect vectors—sand flies, biting midges, and black flies—equine owners and veterinarians can use a variety of management strategies across multiple spatial scales—from the local neighborhood to individual premises, shelters, and animals (Fig. 3)—to reduce the risk and effects of VSV. We encourage individual equine owners, businesses (e.g., boarding stables), and landowners (e.g., small acreage owners, ranchers) to consider their region's relative risk and relevant management strategies for reducing it. Key considerations include 1) the current status and spatial extent of VS outbreaks in the broader region (particularly in states south of yours because outbreaks typically occur there first and then spread north); 2) the risk of VSV-infected equines being introduced to your area (highlighting the importance of biosecurity practices on your premises); 3) whether insect vectors of VSV are active in your region during an outbreak, or could arrive on strong winds from an affected region, and 4) if those insect vectors have suitable breeding/larval/resting habitat in your neighborhood.

If any of these conditions hold, the next step is to determine which of the three biting insect vectors are most likely to exist in your area (Table 1) based on their habitat preferences. Depending on which habitats or vectors are likely in your area during the relevant time of year, next be aware of which times of day they tend to be most active—daytime, nighttime, or at dawn/dusk (Table 2). This will help inform your sheltering strategy. Finally, because some insect vectors are more mobile than others (Table 1), assess their presence not just on or near your premises, but also around the neighborhood and broader area (e.g., whether any streams, irrigation canals, stock ponds, or wetlands are located within a few miles of your premises).

Because insect vectors of VSV can fly or be transported by wind over significant distances, collaborative efforts are needed among owners of neighboring properties to decrease insect habitats, populations, and attraction to an area. In addition, because VSV is easily transmitted between animals, collaborative efforts are needed among equine owners using the same pastures, barns, or stables to take proactive measures to reduce the risk of VS being introduced to a premises (e.g., by transporting an infected animal or contaminated supplies) and preventing its subsequent spread (e.g., by quarantining an infected animal and following strict biosecurity measures).

The complexity and dynamics of a VS outbreak require a coordinated and spatially integrated effort among many individual premises, within and across local neighborhoods, to reduce risk most effectively. Such collaboration requires proactive planning and communication, which could be facilitated by a trusted organization such as homeowners' associations, subdivision boards, or conservation districts. In the absence of such collaboration, VSV risk management is likely to be uncoordinated, incomplete, and less timely. With some, but not all, premises using independent strategies, these efforts will be less effective at limiting the spread of VSV and reducing its impact on the equine community as a whole.

A multilayered approach is also necessary to reduce VSV risk because of the multiple insect vector species and potential transmission routes. A strategy involving multiple layers of protection might include, for example, 1) grazing far from running water, wetlands or other muddy areas, and rock crevices or animal burrows during seasonal or daily peak vector periods; 2) placing propane-fueled CO_2 insect traps between breeding/larval habitat and equine premises; 3) using sand or gravel to fill in muddy areas in the barnyard to improve drainage; 4) reducing biting insects' feeding by sheltering equines during peak vector hours, placing mesh screens over barn windows and doors, and routinely applying insect repellents on animals; and 4) minimizing potential direct contact between animals and contaminated feed/materials/supplies during active clinical cases.

Potential interactions or interdependence between strategies should also be considered. For example, if a horse owner relies on a fly-mask to protect their horse's face and ears from black flies, but not its muzzle, then the animal is still at risk of exposure through bites to the muzzle or through muzzle-muzzle contact with an infected horse across the fence line or a shared water tank. Similarly, if a property owner removes manure from the premises to avoid attracting biting midges, but fails to address muddy areas around water tanks, their manure management efforts might be less effective than they expected.

Numerous knowledge gaps still exist about VSV, including a definitive list of all insect vectors, how widely they range and disperse, where they overwinter, how these characteristics might shift in a changing climate, and how effective various combinations of risk management practices are at the neighborhood, premises, barn, and animal level [103,118]. We cannot guarantee that any one management practice will reduce VSV risk, or that even the most effective combination of practices will prevent all cases of VS disease. On a positive note, however, several management practices

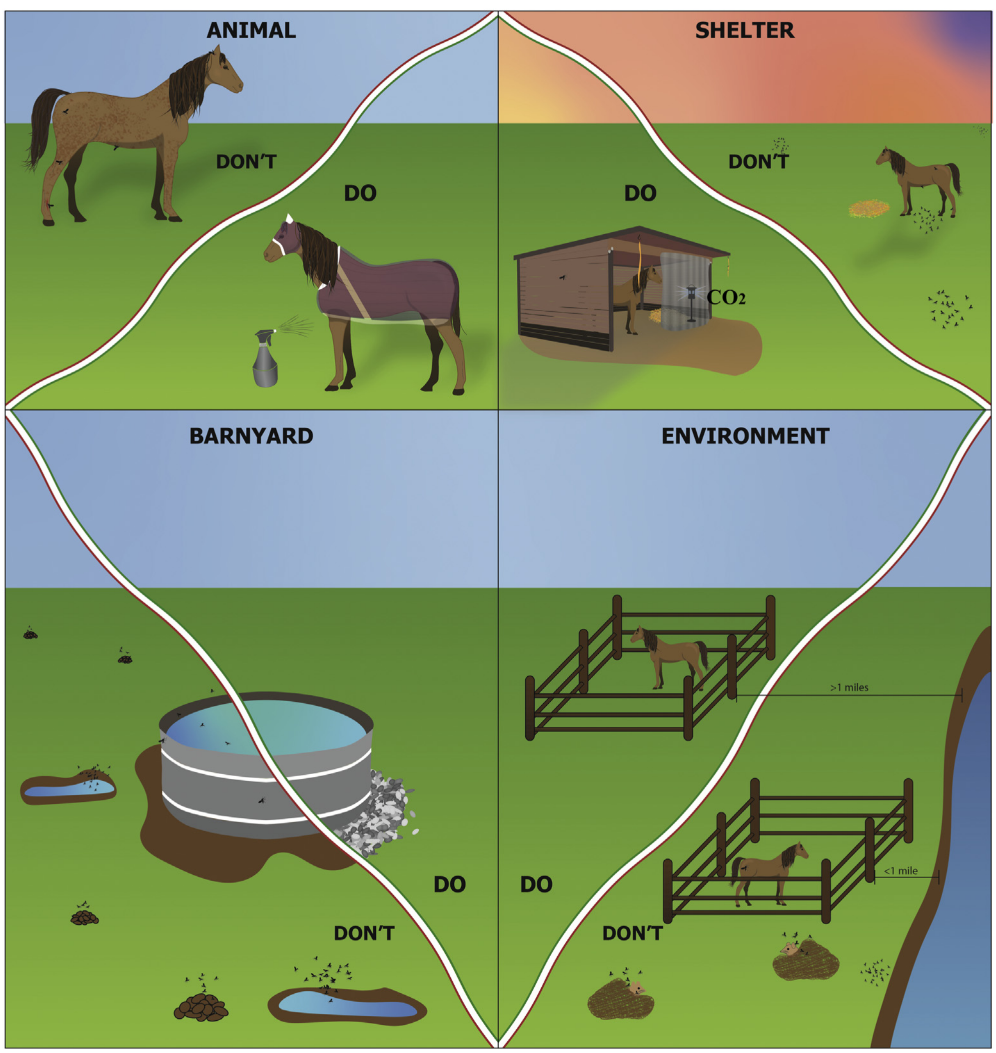

Fig. 3. Proactive management strategies (labeled "DO") at the animal, shelter, barnyard/premises, and environment/neighborhood level that should help reduce pressure on equines from biting insects known to transmit vesicular stomatitis virus (VSV). Each "DO" is contrasted against a "DON'T," to show poorly managed conditions that may increase the risk of equines contracting VSV [graphic art by Victoria Rhodes].

are relatively straightforward to implement—for example, not grazing near streams, irrigation canals, and wetlands after peak runoff as water levels begin to fall and mud becomes exposed; avoiding pastures with rock crevices or animal burrows during peak sand fly season; providing three-sided shelters or bringing equines indoors during peak vectors hours; covering barn windows with fine mesh screens and keeping barn doors closed during high-risk hours; and practicing biosecurity measures to avoid introducing and spreading VSV among equines on a premises. These management practices can also help reduce other insect pests and diseases, thus offering some "no-regret" strategies for keeping equines safe and healthy.

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