Integrated management of blood-feeding arthropods in veterinary teaching facilities – Part 2: overview of control methods against adults and immature stages

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M.-F. Humblet [(1)*], B. Losson [(2)] & C. Saegerman [(3)]

(1) Unit Biosafety, Biosecurity and Environmental Licences, Department for Occupational Protection and Hygiene, University of Liège, Quartier Vallée 2, Avenue de Cureghem 7A, B42, B-4000 Liège, Belgium

(2) Laboratory of Parasitology and Parasitic Diseases, Fundamental and Applied Research for Animals and Health Unit (FARAH), Faculty of Veterinary Medicine, University of Liège, Quartier Vallée 2, Avenue de Cureghem 6, B43, B-4000 Liège, Belgium

(3) Veterinary Science Epidemiology and Risk Analysis Research Unit (UREAR-ULiège), Fundamental and Applied Research for Animals and Health Unit (FARAH), Department of Infectious and Parasitic Diseases, Faculty of Veterinary Medicine, University of Liège, Quartier Vallée 2, Avenue de Cureghem 7A, B42, B-4000 Liège, Belgium

*Corresponding author: mfhumblet@uliege.be

Summary

Numerous arthropod species are involved in the vector-borne transmission of pathogens either to animals and/or to humans. Part 1 of this paper was dedicated to a review of these species, and their role in the transmission of pathogens in North-western Europe. This part will discuss the different anti-arthropod control methods, which are either general, used as good management practices, or arthropod-specific. The majority of these measures are efficient against several arthropod groups. Management of the environment is crucial for controlling the immature stages of winged arthropods, fleas and lice, but also ticks. Spraying pesticides should be considered carefully, because of the risk of emergence of resistance and the negative impact on the environment and non-targeted insects. Monitoring of haematophagous arthropods is useful when considering its use in the validation of control measures, the follow-up of endemic populations, vigilance for emergence of new species, and the detection of pathogens and, indirectly, resistance to chemicals. Monitoring also helps to determine the most appropriate timing and location for implementing control measures. It is strongly advised to combine control methods targeting adults and others addressing immature stages. Even if challenging, their combination under an integrated pest management programme should be preferred. Indeed, integrated vector management aims at making vector control more efficient, cost-effective, ecologically sound and sustainable.

Keywords

Breeding site – Control of adult stage – Control of immature stage – Haematophagous arthropod – North-western Europe.

Introduction

The role of haematophagous arthropods as potential vectors of animal and zoonotic pathogens was described in Part 1 of this publication series (1). The frequency of outbreaks of (re)emerging vector-borne diseases is increasing in Western Europe; indeed, several arthropods are invasive species (e.g. *Aedes albopictus*) and well-known vectors of infectious diseases such as dengue or chikungunya have been introduced to Europe (2). The geographical distribution of some arthropods has increased significantly, e.g. the hard tick species *Ixodes ricinus*, *Rhipicephalus sanguineus* and *Hyalomma marginatum* (3, 4, 5). It is therefore crucial to develop a preparedness programme and to disseminate knowledge, expertise and adequate control tools, to tackle efficiently and rapidly these vectors and the pathogens they transmit.

After reviewing the main haematophagous arthropod vectors of interest in North-western Europe in Part 1 of this publication series (1), Part 2 summarises the main control methods for haematophagous arthropods, which are either general or arthropod-specific. This is the first step towards the introduction of the 'integrated vector management' concept, which aims at optimising vector control by making it more efficient, cost-effective, ecologically sound and sustainable (6). The last section of Part 2 will emphasise aspects of monitoring, and its importance at different levels in veterinary facilities where domestic livestock and companion animals such as dogs, cats and rabbits can be hospitalised.

Control of arthropods

The main objective of arthropod control is to keep them at acceptable densities, to minimise contacts with potential hosts and to prevent their bites. In the majority of cases, it is impossible, even in closed and contained systems, to eradicate arthropods completely, except maybe for ticks, fleas and lice. Nevertheless, total eradication of a vector is often required to eradicate an infectious disease in an epidemic context or when the risk to public health is high. Such eradication can be conducted at the farm, national or even regional level; for example, an *Aedes aegypti* eradication programme was efficient in controlling yellow fever and dengue throughout the American tropics during the 20th century (7).

Control measures will be developed for three categories of haematophagous arthropods, as emphasised in Part 1 of this publication series (1): a) winged arthropods, b) non-flying insects (such as fleas, lice and keds) and c) ticks. As mentioned above, control measures are either general or vector-specific.

Control of winged haematophagous arthropods (mosquitoes, flies [including black flies and sandflies] and biting midges)

In the control of winged haematophagous arthropods, the objective is to reduce their number and limit contacts with infectious and noninfected sick animals. This is of particular importance in isolation premises, because the 'escape' of a pathogen by way of vectors might have severe consequences.

Control measures against adults

Physical control measures

Keeping animals indoors and/or providing shelter at critical hours can protect against insects mostly active outdoors such as sandflies and black flies (8). Such measures are especially relevant for pastured horses because, during the vector season, cattle remain on pasture and dogs are often kept in kennels. Fly masks and fly sheets are widely used to protect horses from fly bites.

Within facilities, keeping doors closed at all times is the first elementary measure. A double doorway system can reduce the entry of winged arthropods into premises, which is important when considering teaching laboratories or isolation facilities (9).

Window and door screens are efficient as a physical barrier maintaining some natural ventilation (Fig. 1). Mesh size influences screen efficiency. Commonly sized nets are efficient against mosquitoes, flies and tabanids, while a smaller mesh size (below 0.4 mm^2) is required to control biting midges, black flies and sandflies (8, 9, 10, 11). However, nets of small mesh size become fouled rapidly in a dusty environment (9). The use of long-lasting insecticide-impregnated nets could be an alternative, as shown to be effective in malaria control programmes (12). Their efficacy is arthropod-dependent, e.g. variable towards *Culicoides* biting midges but effective in excluding sandflies (9, 13, 14, 15, 16, 17). A larger mesh size may prevent efficient contact of vectors with insecticide. Furthermore, the effects of long-term exposure to such devices have not been extensively studied, so a risk of toxicity should not be disregarded (18, 19).

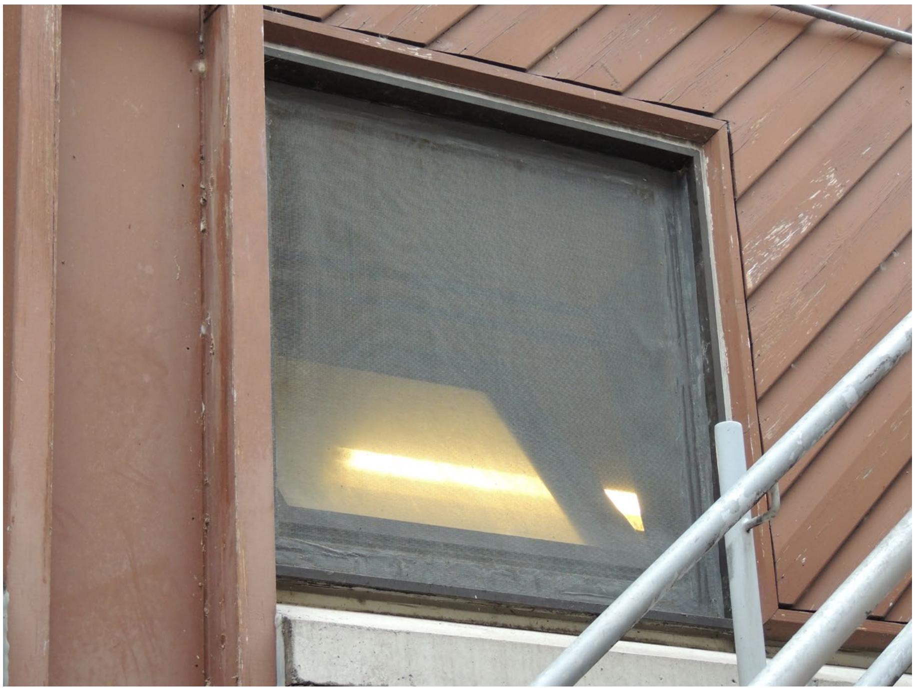

Fig. 1

Screen on the window of a hospitalisation unit for ruminants
(Faculty of Veterinary Medicine, University of Liège, Clinic of Ruminants, Liège, Belgium)

Exhaust openings of isolation facilities could be equipped with high-efficiency particulate absorbing (HEPA) filters, but this would worsen the fouling problem, especially in large animal housing, and generate substantial maintenance costs. The ideal screening material should not impair ventilation and be relatively resistant, especially to corrosion if used in a humid environment. Table I presents the characteristics of different screening materials. Screens should be inspected regularly for tears and holes and cleaned once a month, especially in dusty environments (9).

Table I

Comparison of netting materials for window and door screens in the control of adult flying haematophagous arthropods, i.e. mosquitoes, biting midges and flies (including sandflies and black flies)

Material composing the net	Reduction of ventilation	Resistance to corrosion	Resistance to damage	Cost	Durability	References
Fabric – cotton	Up to 70% (high disadvantage)	not applicable	high disadvantage	high benefit	high disadvantage	10, 20
Metal – stainless steel or copper	30–50% (mean disadvantage)	high benefit	high benefit	high disadvantage	high benefit	10
Synthetic						
Plastic	Up to 35% (high benefit)	not applicable	mean benefit	high benefit	high benefit	10
Nylon	high benefit	not applicable	mean benefit	high benefit	high benefit	20
Polyethylene	high benefit	not applicable	mean benefit	high benefit	high benefit	10
Polyester	high benefit	not applicable	mean benefit	mean benefit	high benefit	20
PVC-coated fibreglass	high benefit	not applicable	high benefit	mean benefit	high benefit	10

PVC: polyvinyl chloride

high benefit

mean benefit

high disadvantage

mean disadvantage

not applicable

Although efficient against mosquitoes, biting midges and sandflies, ceiling fans are not the best option in large animal premises, for economic and safety reasons, especially with horses (9, 11, 21, 22).

More or less arthropod-specific traps might show some efficacy in reducing insect populations, but generally they are more useful in validating control measures, surveying insect population dynamics and detecting the potential emergence of new species (23, 24). Stable flies are attracted by olfactory stimuli such as carbon dioxide, ammonia and phenylpropanoid compounds, and by visual stimuli such as white colour; a combination of both types of stimuli improves the catching process (25, 26, 27, 28).

Traps aimed at capturing horse flies, e.g. the H-trap, are effective when placed around animals in pasture (29). The most appropriate trapping method for *Culicoides* biting midges is the Onderstepoort Veterinary Institute (OVI) light trap (30). Carbon dioxide, heat (temperature), light and octenol attract mosquitoes (31). Numerous types of mosquito trap are available, such as the carbon dioxide-baited light trap, the BG-Sentinel trap, the Centers for Disease Control and Prevention miniature light trap (CDC-LT) and the mosquito-oviposition trap (32, 33, 34). Light traps are not the best solution and should be placed far from animals because of their attracting effect (35). Regarding sandfly trapping, effective devices include light, bait, sticky (Fig. 2) and flight traps; electrocutor traps equipped with ultraviolet (UV) lamps (Fig. 3) are recommended in particular for the control of *Phlebotomus papatasi* (9).

Fig. 2

Flies stuck on sticky paper placed in the room dedicated to feed (pellets) storage and preparation of nursing bottles for calves (Faculty of Veterinary Medicine, University of Liège, Clinic of Ruminants, Liège, Belgium)

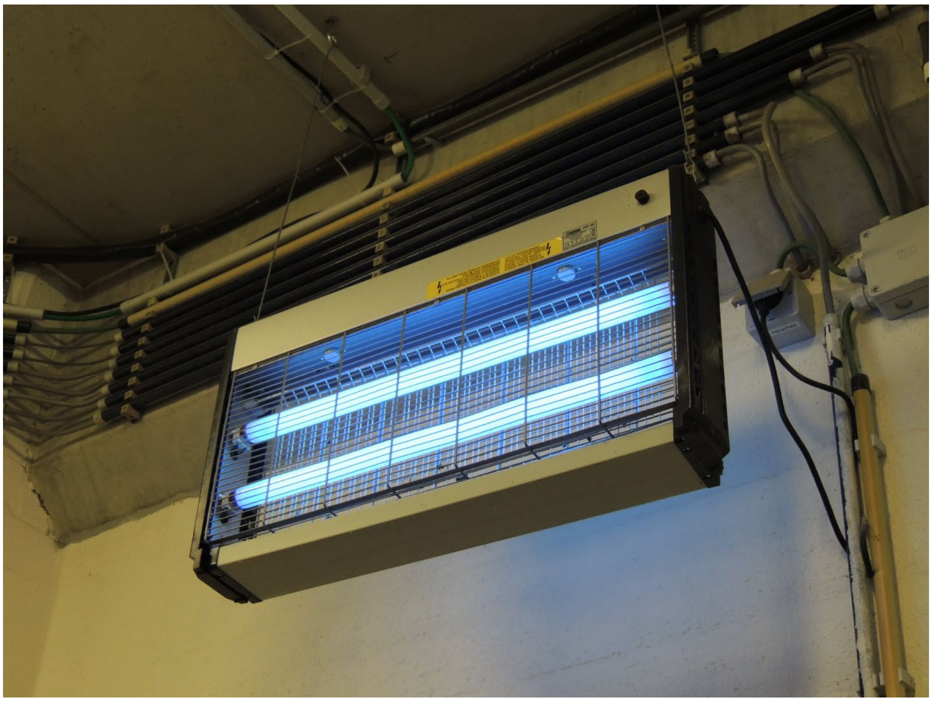

Fig. 3

Electrocutor with ultraviolet light located in the surgery room for small ruminants (Faculty of Veterinary Medicine, University of Liège, Clinic of Ruminants, Liège, Belgium)

As mentioned above, the reduction of populations is not the main objective of trapping although, under some circumstances, removal trapping helps to reduce certain populations (24). For example, solar-powered mosquito trapping systems are used for malaria control, as well as sticky adulticidal oviposition traps to control *Aedes*-borne diseases (36).

Chemical control measures

Chemical control of adults relies on the application of insecticides in the environment or on animals themselves, for a repellent and/or knockdown effect. A variety of products are available on the market and under different formulations for environmental use (e.g. residual sprays, toxic baits, area sprays, fumigation products) or as repellents (e.g. spot-on, impregnated collars or ear tags) (37).

Environmental application of insecticides

Environmental insecticides may pose a hazard to humans and animals and are often non-selective because they kill non-targeted insects as well (37). Long-term use may lead to the emergence of resistant arthropod populations (37, 38).

Space sprays emit fine mists of insecticide that kill adult insects through direct contact (39). They are often used when arthropod densities are high and their immediate killing is required, such as during disease outbreaks or when insects pose a public health threat and nuisance (10). Given its short duration, the procedure needs to be repeated (40). The best time to conduct space spraying is during the cooler part of the day, such as the early morning or evening, and when targeted insects are more active, e.g. during the evening hours for most mosquitoes (9). Sprays can be used for treatment of animal transport vehicles in order to prevent the potential spread of arthropods from one area to another; this process became mandatory, for example, in Europe during the bluetongue outbreak that occurred in 2007 (41).

Residual sprays are insecticides that remain active over extended periods of time (12, 42). They are applied on insect resting places (barn walls, ceilings, rafters, calf hutches and animal shelters) or on critical sites such as drainage grids (43, 44, 45). The efficacy of residual sprays largely depends on fortuitous contacts of insects with treated surfaces (37).

In Europe, the only chemicals authorised as mosquito adulticides are pyrethroids (permethrin-derived); other chemicals such as organophosphates have been banned from use (46). Resistance has been reported among mosquitoes, such as *Aedes aegypti* and *Ae. albopictus*, and stable flies in Europe (47, 48).

Direct application on animals

Insecticides can be applied directly on animals, as pour-on or spot-on formulations, dips, dusting powders and sprays, to protect them from biting vectors (49, 50, 51, 52, 53). Insecticide-impregnated collars and ear tags have shown some efficacy against, respectively, sandflies and horn flies (54, 55).

In North-western Europe, pyrethroids are widely used insecticides registered for protecting both small and large animals against flying arthropods by direct application (56). Deltamethrin-based medicines would be the most effective against *Culicoides* spp., although they only seem to reduce, and not completely prevent, the biting risk when applied on horses and sheep (16, 57). Black flies and sandflies are susceptible to pyrethroids (44, 58). For dogs, deltamethrin-impregnated collars provide a repellent effect towards sandflies lasting from one week to over six months (59). The efficacy of pyrethroid pour-on products against tabanids seems to be limited, while insecticide-impregnated ear tags and head collars are quite successful repellents (60, 61).

Preparations containing N,N-diethyl-3-metatoluamide or N,N-diethyl-3-methylbenzamide (DEET), widely used in human medicine for their repellent action against mosquitoes and other arthropods, should be used carefully in veterinary medicine, because they can be toxic to dogs and cats (62). However, DEET showed some efficacy in repelling tabanid flies when applied on horses in Switzerland (63).

Biological control

The biological control of adult arthropods involves the introduction of natural pest enemies such as parasites and pathogens to the environment (10).

Natural predators of adult arthropods such as birds (e.g. swallows) and bats help in reducing insect populations (64). Nevertheless, birds are potential vectors of pathogens such as *Salmonella* spp., *Campylobacter* spp. or *Clostridium difficile* (65, 66, 67). They also introduce red mites (such as *Ornithonyssus* spp. and *Dermanyssus* spp.) to premises (68, 69); these mites can attack mammals in the absence of their avian hosts, and cause dermatitis in horses, dogs, cats and humans (70). If swallows are allowed inside a building, they frequently pick up straw to build their nests, and could play a role in the transmission of pathogens between animals. Their presence should be avoided inside buildings, but allowed around them, through the implementation of artificial nests, for example, in order to maintain an ecological equilibrium. Table II summarises some examples of control methods for winged haematophagous arthropods of interest.

Table II

Examples of methods aimed at controlling adults of winged haematophagous arthropods of interest, i.e. mosquitoes, flies (including black flies and sandflies) and biting midges

Categories of control measures/tools	Targeted arthropods	References
	Physical control measures	
Keeping animals indoors at critical hours	Sandflies, black flies	8
Fly masks and fly sheets used for horses	Flies	–
Keeping doors closed at all times	All	–
Double doorway system	Mosquitoes, flies	9
Window and door screening		
– regular mesh size	Mosquitoes, flies and tabanids	8, 9
– mesh size below 0.4 mm^2	Biting midges, black flies, sandflies	8, 9
– long-lasting insecticide-impregnated nets	Mosquitoes, sandflies (variable for biting midges)	9, 13, 14, 15, 16, 17
Ceiling fans	Mosquitoes, biting midges, sandflies	9
Traps	Biting midges, horse flies, mosquitoes, sandflies	9, 26, 28, 29, 30, 31, 32, 33, 34
	Chemical control measures	
Environmental application of insecticides (space sprays, residual sprays)	All	37, 39, 40
Direct application of chemicals on the animal itself (repellent and/or acaricide effect)		
– dips, dusting powders, sprays, spot-on, pour-on, ear tags	All	49, 50, 51, 52, 53
– insecticide-impregnated devices such as ear tags, collars	Sandflies, horn flies	54, 55
	Biological control measures	
Natural predators (birds, bats, etc.)	–	64
Natural pest enemies	–	10

mm^2: square millimetre

Control measures against arthropod immature stages

Control of breeding sites and larval habitats

Control of immature stages consists of reducing sources, i.e. eliminating or at least reducing larvae biomass and larval habitats (36). It relies mainly on environmental management of vector habitats, using: a) modification, i.e. long-lasting physical transformation, b) manipulation, i.e. temporary changes to provide conditions unfavourable to vector breeding, and c) changes to human and/or animal facilities and/or behaviour (in order to reduce human/animal–vector–pathogen contacts) (36). Source reduction is easier when egg-laying sites are well identified and specific, as is the case for mosquitoes (71).

Immature stages of mosquitoes

Mosquito eggs can develop in less than 1 cm of standing water and only require water for 4–14 days for maturation, depending on the abiotic conditions (72). The drainage of water standing for more than 96 hours is thus essential to block egg hatching (73).

Environmental modifications reduce populations of adults and extend generation times as females spend more time searching for egg-laying sites (10, 72, 74, 75):

- Remove, cover or overturn small containers as much as possible (holes can be drilled)
- Close, screen or cover water-storage containers
- Fill mosquito-breeding sites (water holes etc.) with soil or stones
- Drain appropriately to prevent water standing for more than 96 hours.

Environmental manipulation includes (10, 72, 74):

- Water level fluctuation (30–40 cm) every seven to ten days in large water reservoirs (larvae are stranded at the margins of reservoirs and irrigation water, and dislodged from vegetation). The interval between fluctuations must be shorter than the lifespan of larvae;

- Reduction of the growth of plants along margins, which will prevent larvae from finding shelter between them;

- Removal of water plants that provide hiding places for larvae from fish predators;

- Clearing of vegetation where necessary, to promote evaporation and drying up of water puddles;

- Weekly flushing to wash away eggs, larvae and pupae or strand them on the banks.

'Standing-water mosquitoes' such as *Culex pipiens* prefer water in ornamental ponds, drains or natural waterways and water containing organic pollution (manure and dairy runoff) (76). Livestock watering ponds may thus become perfect breeding sites. Indeed, animal waste provides nutrients to the water and hoof prints create puddles where mosquitoes may breed (77).

'Container mosquitoes' such as *Aedes albopictus* prefer containers filled with clean water, such as tree holes and human-created containers, e.g. buckets, tyres, garden receptacles, water storage containers, construction materials, roof gutters, flower vases, potted plant saucers, cattle troughs and pet dishes (78, 79, 80).

The majority of modifications and manipulations have consequences for the environment, and arthropod control can lead to partial environmental destruction with a negative impact on other species; for example, the canalisation of large rivers in central Europe to reduce flooded areas had a negative impact on wildlife (72).

Immature stages of Culicoides *midges*

Adult midges prefer to lay their eggs in wet organic matter, such as mud around settling ponds, decaying vegetation and manure, to prevent the immature stages from drying out. Controlling moisture and stagnant water is essential to reduce their number and help to reduce the proximity of insect eggs to livestock (81). The strict enforcement of hygiene measures, through the elimination of nesting substrates and careful management of manure (faeces, silage residues, etc.), is also essential to control populations of biting midges (81, 82).

Immature stages of flies (stable flies, horse flies and horn flies)

Adult flies lay eggs in wet organic matter, such as fresh manure and spilled feed (83). Adults and larvae feed on numerous sources including blood, flesh, carrion, faeces, manure, organic waste products and decomposing vegetable matter (83, 84). Fly infestations are due to inadequate hygiene and poor management of manure, feed and animal housing; even effective fly control methods cannot compensate for poor hygiene (37). It is essential to eliminate fly breeding sites, to prevent contact with food sources and utensils, to remove manure frequently and to allow rapid drying of stored manure (flies avoid laying eggs on its crusted top) (85, 86). Decreasing soil moisture dramatically reduces fly biomass (85, 86).

Immature stages of sandflies

Source reduction is hardly feasible because sandfly larval sites cannot be easily identified (87). Nevertheless, some basic actions such as filling cracks and crevices in walls, ceilings and floors, and clearing or paving outdoor areas can eliminate some sandfly breeding and resting sites (44). Removing organic waste, garbage and unwanted vegetation helps reducing sandfly breeding, as well as the removal or drying out of moisture around facilities (8, 88, 89). Destroying the habitat of reservoir hosts, such as rodents, is also effective (88). Maintaining strict hygiene in dog kennels by frequently removing dog faeces (ideally this should be performed daily) and maintaining low humidity helps to reduce sandfly breeding, because many of them lay eggs on animal faeces (90).

Chemical control: use of chemical larvicides

Chemical larvicides can be sprayed directly on breeding sites to kill larvae, but should be used carefully because they also affect non-targeted insects such as pollinating species (91). They should be dedicated to 'hot spots' and where populations of non-targeted insects will only be slightly affected (92).

Chemicals such as organophosphates, carbamates and pyrethroids can be used against mosquito larvae (93). The application of a thin oil film (mineral oil) to the water surface kills larvae by suffocation (94), but such a technique is only applicable to small water surfaces such as wells. The use of chemical larvicides for mosquito control should only be considered for sites that cannot be drained or filled and where other source reduction methods have failed or cannot be implemented (10).

Environmental control of horse flies is difficult, because larval habitats are not well identified (61, 95).

Chemical larvicides may also be used for the control of fly larvae, especially horn flies; they are not as efficient for the control of stable flies which develop in many sites other than fresh manure (feed mixing areas, silage holding areas and feeding lanes) (96). Oral larvicides are sometimes used in cattle to prevent the development of flies in manure, but one should be aware of the risk of resistance development and of the negative effect on non-targeted arthropods (86).

Insect growth regulators (IGRs) interfere with the normal development of insects, resulting in their death before reaching the adult stage (97). They are of particular interest where insects have developed resistance to other chemical larvicides or where any negative effect on the environment should be avoided. Most IGRs have low toxicity to the environment and to vertebrates, compared with other chemical larvicides, and are more specific, but they can disturb the development of various species of arthropods living on breeding sites of targeted arthropods and have negative effects on immature stages of aquatic insects and crustaceans (98).

Biological control: bacterial larvicides

The biological control of larvae can rely on the use of natural predators such as fishes or dragonfly larvae (99, 100). When ecological equilibrium is reached, the populations of natural predators will increase and the trophic chain will regulate vector populations.

Bacterial larvicides, such as toxic products of *Bacillus thuringiensis* H-14 and *B. sphaericus*, have been used in Europe for controlling mosquito larvae (101). *Bacillus sphaericus* inhibits hatching of sandfly eggs (102). Granules of *B. thuringiensis israelensis* can be spread over a flood-prone area of pasture; they are toxic to mosquitoes, some flies such as black flies and midges (43, 103, 104, 105). The use of bacterial larvicides is an excellent tool to control black flies, because larvae are concentrated in easily identifiable and specific habitats, which is not the case for biting midges, horse flies and sandflies (60, 106, 107). Examples of measures and tools to control immature stages of winged haematophagous arthropods are summarised in Table III.

Table III

Examples of methods aimed at controlling immature stages of winged haematophagous arthropods of interest, i.e. mosquitoes, flies (including black flies and sandflies) and biting midges

Categories of control measures/tools	Targeted arthropod immature stages	References
	Environmental control of breeding sites and larval habitats	
Environmental modifications		10, 72, 74, 75, 81
– remove, cover or overturn small containers	Mosquitoes	
– close/cover or screen water-storage containers	Mosquitoes	
– fill mosquito-breeding sites	Mosquitoes	
– drain to avoid standing water	Mosquitoes, biting midges	
Environmental manipulations (temporary changes)		10, 72, 74
– water-level fluctuations in large water reservoirs	Mosquitoes	
– reduction of the growth of plants along margins	Mosquitoes	
– remove water plants	Mosquitoes	

– clear vegetation when necessary – weekly flushing	Mosquitoes, sandflies Mosquitoes	
Control (decrease) moisture in and around facilities	Biting midges, stable flies, horse flies, horn flies, sandflies	8, 81, 85, 86, 88, 90
Strict hygiene	Biting midges, stable flies, horse flies, horn flies	37, 81
Careful management of faeces (quick removal) and manure (frequent removal, quick drying of stored manure)	Biting midges, stable flies, horse flies, horn flies, sandflies	82, 85, 86, 90
Good management of feed and animal housing	Stable flies, horse flies, horn flies	37
Removing organic waste, garbage	Sandflies	8, 88, 89
Filling cracks and crevices in walls, ceilings and floors, and clearing or paving outdoor areas	Sandflies	44
Destruction of habitat of reservoir hosts (e.g. rodents)	Sandflies	88
Chemical control		
Spraying of chemical larvicides on breeding sites ('hot spots')	Mosquitoes, horn flies	91, 92
Oral larvicides (cattle)	Stable flies, horse flies, horn flies	86
Insect growth regulators	Horn flies	97, 98
Biological control		
Natural predators (fishes, dragonfly larvae)	Mosquitoes	99, 100
Bacterial larvicides (*Bacillus thuringiensis* H-14 and *B. sphaericus*)	Mosquitoes, black flies > biting midges, sandflies	43, 60, 101, 102, 103, 104, 106

Control of fleas and lice

The control of fleas and lice should be performed through an integrated approach including more than one control measure. In order to be efficient, it requires the treatment of affected animal(s) and contact animals; furthermore, such treatment must be combined with environmental control for fleas (108, 109).

Physical control measures

Fleas and lice are generally introduced then dispersed within facilities by introduction and movements of an infested animal or sharing infested equipment (110). Once fleas have been introduced to a facility, the main risk of infestation of non-infested animals comes from the environment (108). The physical separation and treatment of infested animals reduce accidental transfer to other animals (111). It is worth mentioning that humans can be infested by fleas and/or act as carriers and infest other animals (112).

Fleas are transmitted to another animal through close contact, or from an infested environment, where immature forms are quite resistant (110). The elimination and/or treatment of potential developmental sites is a crucial point of flea control. In small animal environments, adults, eggs, larvae and cocoons can be effectively removed by mechanical cleaning of pet cages, beds and bedding, for example sweeping, washing and vacuuming bedding areas and/or carpets regularly; removing animal bedding helps to reduce infestation pressure as well (110, 113). The elimination of rodents around facilities minimises potential contact with vectors (114). For large animals such as pigs, removing bedding also helps to reduce infestation pressure; indeed, pigs may also become infested by cat, dog and human flea species (111).

Lice are transferred between hosts by direct contact, or through fomites such as straw bedding, blankets and grooming equipment (115). Some lice and eggs may drop onto bedding or may be rubbed off, along with hair, onto fences and feed bunks (116). Cattle may become infested from contaminated bedding, bunks, sheds or trucks (117). Lice are permanent ectoparasites (118). Lice infestations are more frequent in animals subjected to overcrowding and poor hygiene, poor feed quality, gestation and underlying health issues (109, 115, 119). Removal and frequent changes of bedding can help to reduce their development. Clipping an infested animal’s long, heavily soiled or matted coat can immediately reduce the parasite burden and allow topical products to be distributed evenly (117). Newly purchased stock should be isolated and treated for lice and other ectoparasites before introduction to the herd (117). Regular inspection of small animals’ bedding, collars, grooming tools and other similar objects in their environment is necessary. Bedding should be washed frequently or treated with an appropriate insecticide spray (110). As management is also important in infestation by these ectoparasites, different stress factors should be reduced, for example by avoiding overpopulation, respecting hygiene, reducing stress and avoiding malnutrition (115).

Chemical control measures

For flea control, both animals and environment should be treated; indeed, 95% of the flea population is present in the environment as eggs, larvae, nymphs and pre-emerged adults. By contrast, treating animals is sufficient for lice control.

Insecticides should be directly applied to infested animals, and all their contacts, even those not infested. Flea control requires repeated applications, for which two or more treatments, 10–14 days apart, or long-acting insecticides are needed, as eggs are protected from the insecticide and may survive the first treatment (120, 121). The preventive use of insecticides is generally implemented for flea control in dogs and cats. Control of lice is generally easier, and can be achieved after two or three treatments (122).

Many ectoparasiticides are active against both fleas and lice, such as pyrethroids (123). Other active ingredients belonging to several families are efficient also, such as neonicotinoids, organophosphates, pyrethroids, phenylpyrazolates or nitroguanidines (123, 124). Isoxazolines are a more recent family of neurotoxic molecules that have both insecticide and acaricide effects (125); they have an inhibitory activity on glutamate and gamma-aminobutyric acid gated chloride channels of the invertebrate nervous system (126). Pyrethrin-derived substances and amitraz (not active against fleas) are toxic to cats; they should not be used off label. Specific medication contains the active compound at a very low concentration or as a slow-release formulation (109, 127).

Multiple formulations are available for application on animals, such as pour-on, spot-on, collars, sprays, injectable, wipe-on, powders and oral medications (117, 128). Pour-on formulations are popular for cattle because they are easy to apply without stressing the animals too much and do not require a withdrawal period for meat and milk; devices such as ear tags can also be used (49, 129). For horses, sprays are the most suitable method for lice control and for small animals, spot-on products are widely used (128, 130).

When treatment of the environment is recommended, insecticides should be applied, at the minimum, to the floor, lower walls and pet bedding area (114). Given that these molecules may be toxic to humans and animals, protective measures should be implemented, such as following label directions and wearing adequate clothing (long-sleeved shirts and long trousers) and adequate protective equipment (e.g. safety goggles to protect against splashes, as well as waterproof elbow-length gloves, apron and footwear) (131, 132).

Insect growth regulators, such as lufenuron or pyriproxyfen, block flea reproduction through residual control and fewer applications (133). Lufenuron prevents eggs from hatching, when used alone or associated with adulticides (134). Table IV summarises examples of control measures against fleas and lice.

Table IV

Examples of methods aimed at controlling fleas and lice

Categories of control measures/tools	Fleas	Lice	References
	Physical control measures		
Physical separation of infested animals			111
Isolation (and treatment) of newly purchased stock before introduction to the herd			117
Avoid moving infested animals			110
Avoid sharing infested equipment			110
Regular mechanical cleaning (sweeping, washing and vacuuming) of pet cages, beds and bedding, carpets			110
Regular inspection of small animals' bedding, collars, grooming tools, etc.			110
Frequent removal of livestock bedding			113, 135
Elimination of rodents around facilities			114
Reduce stress factors – avoid overcrowding – respect hygiene – avoid malnutrition and ensure good feed quality – care for underlying health issues			115, 119
Clipping an infested animal's long, heavily soiled or matted coat			117

Chemical control measures			
Treatment of the infested animal (and contacts) with an insecticide (pour-on, spot-on, collars, sprays, injection, powder, ear tags, etc.)			49, 117, 120, 121, 128, 130
Preventive use of insecticide (dogs and cats)			124
Treatment of the environment with an insecticide, i.e. floor, lower walls and bedding area (dogs and cats)			114
Use of insect growth regulators			133, 134

Control of ticks

The control of ticks relies on several pillars: management of hosts (both domestic and wild), application of chemicals (that have a repellent or a direct acaricide effect), landscape management and prevention of tick-borne infections through vaccination, when available (117). For example, in Europe, vaccines against Lyme disease and piroplasmosis (*Babesia canis*) are available for dogs in several countries (136, 137, 138).

Management of tick hosts

Ixodes ricinus ticks feed on a wide range of hosts including wild hosts such as rodents and deer (139). Birds and rodents are frequent hosts for immature stages (140). The exclusion of wild hosts is an essential part of tick control. One can implement several actions to reduce the presence of rodents, for example reducing nesting and hiding opportunities, covering holes or protecting feed (141). Animals at pasture can be protected by fencing to keep them from accessing wooded and at-risk areas (Fig. 4). The pasture perimeter can be mowed to keep mice and tick populations low around pasture margins. The management of wild hosts is very difficult, however, except in very limited areas (142).

Fig. 4

Fencing of pasture to prevent cows from entering neighbouring wooded areas, an environment at risk for ticks. Double fencing creates a buffer zone where vegetation can be controlled in order to avoid a habitat suitable for ticks (Faculty of Veterinary Medicine, University of Liège, pasture of the experimental farm)

Companion animals should not be introduced to wild tick habitat, i.e. grassland, heathland and rough pasture, as well as deciduous and coniferous woodland, where vegetation maintains high humidity (143). A daily check for ticks and their prompt removal is the most important and effective preventive method, especially for dogs and cats (143).

Chemical control

Numerous categories of acaricides are widely used for tick control and as repellents, such as pyrethroids (e.g. permethrin and flumethrin), formamidines (e.g. amitraz), macrocyclic lactones (e.g. ivermectin) and phenylpyrazoles (e.g. fipronil) (53). For dogs and cats, the introduction of isoxazolines has provided convenient oral dosing with long-lasting efficacy (53, 126). Formulations are similar to those described above for fleas and lice, i.e. spot-on, sprays, collars, powders or pour-on (large animals). For livestock, acaricides can be provided through slow-release devices such as ear tags or implants and boluses (53). The residues of boluses can, however, have a negative effect on cattle dung fauna, as has been documented with ivermectin, for example (144, 145).

Landscape management

Landscape management involves making the environment less suitable for the survival of ticks and their wild hosts (53, 146, 147). The creation of a buffer zone at the periphery of small animal yards or large animal grazing areas is strongly recommended, by removing bushes and leaves, clearing tall grasses, trimming tree branches to let in more sunlight and placing a barrier of wood chips or gravel (148). Mowing lawns frequently and removing cover vegetation will reduce the presence of rodents (148). The appropriate fencing of large animal grazing areas will exclude wild large mammals (53). Landscape management must be sustainable in order to limit its potential negative impact on biodiversity and the environment itself.

As *Rhipicephalus sanguineus* often infests indoor areas, kennels should be regularly monitored and treated for infestations (53, 143). Examples of other tick control methods are summarised in Table V.

Table V

Examples of methods aimed at controlling ticks

Categories of control measures/tools	Examples of measures	References
	Management of tick hosts	
Exclusion of wild hosts – rodents	Reducing nesting places	141
	Reducing hiding places	141
	Covering holes	141
	Protection of feed	141
	Frequent mowing of lawns and pasture perimeters	141, 148
	Removal of covering vegetation	148
Exclusion of wild large mammals (e.g. deer)	Fencing of large animal grazing areas	53
Avoidance of tick habitat (grassland, heathland, rough pasture, deciduous and coniferous woodland)	Avoid walking animals in at-risk areas	143

Daily check for ticks	Daily check for ticks and prompt removal, especially for dogs and cats	143
	Chemical control	
Direct application of chemicals on animals (acaricide and/or repellent effect)	Topical formulations (see Table IV – chemical control measures for fleas and lice)	53
	Slow-release devices such as ear tags, implants, boluses (cattle)	
Treatment of indoor areas [(a)]	Regular monitoring and treatment of kennels	53, 143
	Landscape management	
Creation of a buffer zone at the periphery of yards/large animal grazing areas	Removal of bushes and leaves	148
	Clearing of tall grasses	148
	Trimming of tree branches	148
	Barrier of wood chips or gravel	148

(a) especially important for *Rhipicephalus sanguineus*; this tick species can be active all year round inside households if the environment is favourable (149, 150).

Monitoring of haematophagous arthropods

The monitoring of haematophagous arthropods allows: a) validation and eventual adaptation of control measures; b) follow-up of population dynamics; c) vigilance for emerging species; d) detection of pathogens; and e) indirect detection of resistance to chemical insecticides (23, 151, 152). It can also indirectly allow the mapping of breeding sites to target control measures for immature stages. Monitoring pests can allow restriction of chemical treatments to periods of activity (85). Flying haematophagous arthropods are generally monitored through trapping (153).

Animal behaviours, such as stomping, tail swishing, skin twitching and head and ear movements in fly-infested cattle or scratching in flea-infested animals, provide information on the degree of infestation intensity (127, 154). In cattle, ear flicks and stamps/kicks are correlated with the number of flies on the face and legs, respectively (155). The number of cattle tail flicks within a two-minute period measures fly activity, with ten per animal being considered as the economic threshold (156).

Among pastured cattle, the degree of fly infestation can also be estimated by the weekly counting of flies on 15 randomly selected animals (135). A limit of five stable flies per leg has been defined as the economic threshold (135, 157). Horn flies can be counted at mid-morning, when they are resting on the backs and sides of cattle (154).

In terms of monitoring, record keeping is essential in order to follow population dynamics and eventually to adapt preventive and control measures.

Conclusions

Vector control measures are numerous, with very variable efficiency. Their implementation must be adapted to the context and optimised when considering the potential impact on the environment, i.e. chemical adulticides and larvicides should be used rationally and in a way that minimises consequences for non-targeted insects and environmental toxicity. Vector populations should guide management decisions such as when and how to control the pest (158). Monitoring of endemic species and vigilance for the emergence of exotic arthropod species are therefore crucial. Two factors can compromise the sustainability of control measures: introduction of exotic species and emergence of resistance to pesticides within endemic arthropod species (85). These factors frequently lead to disease outbreaks, often amplified by environmental changes (e.g. climatic or local, through landscape fragmentation or irrigation, for example) and socio-demographic changes (e.g. urbanisation, poverty, degradation of medical and veterinary health services, globalisation, etc.) (159, 160). The long-term use of insecticides creates a selection pressure which may lead to the development of resistance in targeted and non-targeted arthropod populations (85). The continuation of research on non-chemical sustainable arthropod control methods is strongly advised.

The combination of measures targeting both adults and immature stages using the integrated vector management concept should be prioritised, in order to increase the effectiveness of the control methods and make them more cost-effective, ecologically sound and sustainable (6).

The control of disease vectors should be performed using a One Health approach, which means involving a transdisciplinary and collaborative approach, considering the host (animal and/or human), the vectors and the environment. The environmental component is too often neglected (161), but this paper has highlighted the importance of environmental management in the control of almost all categories of arthropods. Animal and/or human hosts, blood-feeding arthropods (potential vectors) and environment should be considered as a whole, in order for control plans to be efficient.

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