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Perspective

Mosquito Control: Perspectives on Current Issues and Challenges

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INTRODUCTION

Mosquitoes are nuisances and vectors of disease. Effective mosquito control minimises human exposure to biting and infection risk. Various species transmit a wide range of diseases [1]. The major potentially deadly ones include yellow fever and malaria; serious and sometimes fatal ones include Dengue, Encephalitis (Eastern Equine encephalitis in USA; Japanese encephalitis in Asia [2]); less serious and often not fatal but nonetheless important diseases include West Nile virus (imported into USA in 1999; Ross River virus in Australia [3,4] and south east Asia [5]). Emerging diseases such as Zika virus are a challenge for mosquito control [6].

Problem mosquito species are specific to one or more diseases and so control is challenging. This is because the mosquito life cycles vary considerably between genera and species. For example, some (e.g., *Aedes* spp) lay eggs on damp earth whereas others lay egg rafts on water (e.g., *Culex* spp). Some are found in water containers close to human habitation (e.g., the peri-urban vectors of dengue and Zika viruses); others thrive in freshwater (*Culex annulirostris*) or in saline tidal pools (*Aedes vigilax)* and both are vectors of Ross River virus [7].

Control usually involves repeatedly using larvicides and/or adulticides. For long-term control source reduction is used. That is, mosquito-breeding habitats are removed (in the case of container breeding mosquitoes) or altered to interfere with the mosquito life cycle, reducing the emergence of adult mosquitoes. Repellents may provide control to cause death and/or to prevent biting and may be broadly applied, as in the case of barriers, or used at a personal level as a repellent.

Mosquito control organisations operate at a local, national and international level, sharing information among control and government agencies and providing outreach services. The American Mosquito Control Association is the world premier mosquito control organisation, with international membership and connections with 50 countries. It convenes an international conference each year where current key issues and challenges are presented and discussed. Using the abstracts of presentations at the February 2017 meeting, we have selected the most important current issues and have integrated them into sections that are directly relevant to mosquito control as follows:

- Basic Information
- Control Technology
- Adult Mosquito Control
- Larval Mosquito Control
- Source Reduction
- Management issues

We have added an "Additional Broader Issues" section that extends the perspective to include some additional challenges. We also include some references that are accessible in the literature.

THE ISSUES AND CHALLENGES

Basic information

Emerging diseases and incursions of vectors were key issues. The recent Zika virus outbreaks in parts of South America [8], USA and elsewhere, challenged mosquito control agencies to rapidly respond. The main diseases discussed included: West Nile virus, Zika virus, Chikungunya virus, dengue, malaria and St Louis encephalitis. The main vectors were *Aedes aegypti* and *Ae. albopictus*, although there were several others implicated in transmission. Many presentations described the challenge of the emergence and spread of the diseases and control issues.

Mosquito control is needed if there are nuisance or disease vector mosquitoes within biting range of human populations. To establish the need for control, information is needed about mosquito numbers, species and disease vector status. The traditional method is to set light traps with carbon dioxide, collect and count mosquitoes and identify their vector status [9]. This is not necessarily accurate as different trap types may attract different species. To address this issue trap improvements are discussed below in Control Technology.

The key to control is to understand mosquito biology. The biological aspects discussed were predominantly for adult mosquitoes. Two novel perspectives on oviposition were: the apparent defence of its oviposition site by *Ae. aegypti* to prevent another mosquito species from ovipositing, by attacking it; and oviposition inhibition by the presence of fish semio chemicals (*Cx. tarsalis*). This latter is supported in the literature [10], though whether it can be used in mosquito control remains to be investigated. Also, relatively recent techniques such as: using microsatellites to identify the origin of different populations of *Ae. aegypti* that might show relationships with vector competence; identifying amino acid mutations which could permit or increase vector competence in some *Aedes* spp.

The development of insecticide resistance is a challenge [11,12]. In the case of disease vector mosquitoes, resistance can render treatment ineffective and thus disease or nuisance risk is not reduced. The health consequences can be serious. Challenges include the variability in susceptibility of mosquitoes to insecticides, related to species, regions and active ingredients. There was a suggestion that susceptibility may be reduced (i.e. resistance increased) in agricultural areas, raising concern that agricultural chemicals may be implicated. Having a range of control methods can mitigate or delay the effects of resistance.

Control technology

Mosquito and habitat surveillance and mosquito control was an important component of the conference. Solutions to the issue of inaccurate trap collections included modified trap design and the use of various attractant baits. A relatively recent novel method was to use sugar baited cards to collect mosquito saliva for virus testing in the laboratory [13]. This provides mosquito numbers and species as well as identifying the presence of virus.

Identifying and mapping mosquito larval habitats is a prerequisite for effective control, as focusing on larvae can reduce populations at source? A challenge is dealing with the complexity and size of the spatial data. Packages such as Vector Base (under development) or Fusion tables (free on Google) allow uploads of large data sets and enable visualization of habitat distribution. Integrating ecological, hydrological and entomological information with Geographical Information Systems and remote sensing would enhance the value of the models [14,15].

Applying insecticides can be challenging. For adulticiding it needs to be done when adults are on the wing; for larvicides there may only be a few days opportunity before larvae emerge as adults. These challenges have been addressed traditionally by spraying from helicopter or fixed wing aircraft. Recently the use of Unmanned Aerial Vehicles or drones has been explored [16]. These can identify breeding habitats and the presence of larvaeas well as delivering chemicals. The role of regulations can be challenging. For example, the requirement that drone operators must be qualified pilots, has recently been removed in USA, yet persists in Australia.

ADULT MOSQUITO CONTROL

Aedes aegypti, especially in Florida was a focus, reflecting the importance of the emergence of Zika virus [6]. Several other diseases vectored by *Ae. aegypti* were included (dengue, Chikungunya, Zika, yellow fever). Surveillance was an important issue and included trap design and attractants as noted above.

There are no vaccines available for Chikungunya, dengue and Zika viruses. If insecticides fail (e.g., because of resistance, product failure or delivery failure) there is a need for alternative control. This is a challenge. One alternative that is attracting much interest is the Sterile Insect Technique, in which sterile males are released. New methods are needed. For example, combining the Sterile Insect Technique with other methods such as infection with Wolbachia bacteria to ensure effectiveness [17,18]. Releasing transgenic mosquitoes is another option. The Oxitec method releases genetically engineered males resulting in the death of their progeny [19]. A further challenge is in engaging the public to facilitate acceptance of the methods (refer to Management below).

Other novel control methods included: autocidal techniques, whereby the mosquito becomes the dissemination agent, by carrying dust or being injected with bacteria such as Wolbachia [20]. A novel idea was that injecting cattle with Eprinomectrin (that controls endoparasites in cattle) might also kill anopheline malaria vector mosquitoes. This could be cost effective in cattle-breeding areas, making use of existing procedures.

LARVAL MOSQUITO CONTROL

Larval research focused on surveillance to identify the characteristics of larval habitats [21]. The technology aspect of this was addressed above (Control Technology). A challenge is that some habitats are difficult to access. To survey and treat the many small and widely distributed containers on private property was a challenge, as occupants may not permit access. This is an important issue for managing *Ae. aegypti* and *Ae. albopictus* and the diseases they transmit. The issue of access is discussed later under Management. Direct larval control included issues of repeated surveillance, application of killing agents, and application technologies. The main products discussed included the bio-rationals such as *Bacillus thuringiensis* var *israelensis* (Bti), Insect Growth Regulators and plant extracts with these and others in novel combinations. As with adult control resistance is an issue.

Catch basins and drains are a category of constructed wetlands often associated with peri-urban development. They have potential for mosquito breeding [22], posing risks to nearby populations [23]. However, with suitable design, they may not produce adult mosquitoes, even in wetlands treating secondary treated sewage [24]. A practical challenge is the resources needed to inspect catch basins and to treat, if necessary, as there may be very many in a mosquito control district. For example, in Sacramento-Yolo in California there were over 200,000 sites. Additionally, there is a risk of losing insecticides by flushing after heavy rain, although using multiple tablet or granule formulations may mitigate this. However if mosquitoes are taken into account at the design stage, the need for active management may be minimal.

Source reduction

Indirect control using source reduction is an important component of mosquito management. This was noted mainly in the context of containers and backyard sanitation (emptying water from domestic containers). Source reduction simply means reducing breeding sources. Source reduction can reduce the pressure on other mosquito control resources and provide at least background control. The American Mosquito Control Association refers to it as the "single most effective means of vector control" (p4) [25].

Source reduction can provide long-term effective control and may be suitable for resource-limited programs, as methods can be flexible. In USA source reduction in tidal wetlands is well established. It may involve large construction projects, sometimes to remedy the wetland damage from earlier decades [26,27]. There are less intensive options, also well established, involving minimal modification of wetlands and not requiring heavy equipment [28]. These focus specifically on the essential requirements for mosquitoes and modify the habitat from that perspective.

MANAGEMENT ISSUES

The management system is crucial to developing and implementing an effective mosquito control program. It can enhance control (see Landscape and Land Use Planning below). A key issue was communication and collaboration with the public and other stakeholders and with both state and local government agencies. The challenge of achieving good public information and relations was often stressed, especially in the case of emerging diseases such as Zika virus [29]. The use of social media was mentioned. This is a potentially powerful tool for rapidly disseminating emerging disease and mosquito related information to the public and for receiving feedback to management [30].

Management occurs within a regulatory framework. The specifics were directly relevant to the USA audience, although some basic issues apply more generally. These include the challenges of policy inconsistencies between and within organisations that may inhibit best practice, or at least impede its development. The American Mosquito Control Association has good government contacts and relationships (see for example [31], but this is not necessarily the case everywhere. Building trust and capacity by collaboration helps to meet the challenges and this has been widely recognised [32,33].

ADDITIONAL BROADER ISSUES

We have included the issues of landscape and land use planning, environmental issues and climate change, as they are important for mosquito control. They were not well represented at the conference and this may be because of the overwhelming urgency of responding to emerging diseases. Another reason may be that local agencies do not have the authority to address these issues or institutional processes may be inappropriate.

Landscape and Planning

The nature of the landscape was addressed briefly. Landscape characteristics (e.g., vegetation, wetlands) can limit or enhance mosquito risk and/or support mosquito control. However, landscape designers or planners may beun aware of mosquito control issues and may inadvertently increase the mosquito problem by what might be well meaning but ill-advised decisions. For example, directing storm-water runoff into a wetland intended to enhance the wetland may simply increase mosquito production.

Land use planning

Although landscape structure was recognised as important there was no mention of land use planning. Planning for expanding human settlement, taking account of mosquito habitats, can reduce the risk of increasing mosquito–people interactions. This problem has been recognised in Australia. One reason for its omission may be that mosquito control is often carried out by a specific agency that is not part of a general planning organisation, or, if it is, the various departments do not communicate on this matter. Integrating or at least liaising between land use planners and mosquito management has the potential to provide benefits resulting in fewer diseases or mosquito complaints and minimising any increased need for control.

ENVIRONMENTAL ISSUES

Environmental issues are a concern for mosquito managers, as the environment is their workplace and damaging it would result in adverse reactions to their activities. In the USA source reduction in the early part of the 20th century destroyed many wetlands [35] and this has led to a perception by some people that mosquito control is environmentally destructive. With modern methods (including those that rehabilitate wetlands) this is no longer true [36].

Climate change

Since mosquito distribution and development rates are affected by temperature, rainfall and humidity, changes in climate are likely to affect the distribution and seasonal abundance of mosquitoes and hence disease and nuisance risk. Bai et al., reviewed climate change and mosquito borne disease in China [30]; Rochlin et al., considered the issue in north-eastern USA with implications for health practitioners [31]. That this was not an issue at the conference may be explained by the lack of control that local agencies have over responses to climate change.

CONCLUDING REMARKS

At the conference there were general issues, which were explicit or implied. The unpredictable nature of mosquito outbreaks and disease activity was important. However uncertainty underlies most aspects of science including research into the mosquito system. From our perspective, there were few new issues presented but there were some novel solutions proposed including: control based on mosquito reproduction; virus detection techniques; trapping technology; and delivery of insecticides.

- Several key issues present serious and urgent challenges for mosquito control. These include:The issue of managing incursions of vectors of emerging diseases and the challenge of being prepared for unpredicted outbreaks;

- insecticide resistance and the challenge of keeping ahead with new biological and chemical insecticides or alternative methods;
- The issue of public acceptance in a rapidly changing world and the challenge of communicating effectively with all stakeholders;
- The issue of collaboration and the challenge of building trust and capacity.

In conclusion, the issues and challenges presented at the conference open a wide range of research opportunities relevant to management.

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