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A call to arms: Setting the framework for a code of practice for mosquito management in European wetlands

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Abstract

1. Wetlands provide multiple services to human societies. Despite policies dedicated to their protection, current European policies do not address the need to balance mosquito management approaches to mitigate dis-services to human health and well-being while ensuring that wetland conservation goals are met.
2. Herein, we outline criteria for consideration when developing mosquito control programmes in European wetlands that will allow managers and public health authorities to adopt effective and ecologically sound approaches.
3. *Synthesis and applications*. The proposed code of practice provides practical advice to local authorities and those involved in mosquito control in order to design an integrated mosquito management strategy that aligns with current environmental legislation. Although this code of practice was developed by European experts, it is transferable to other geographical contexts, integrating the expertise and knowledge of local stakeholders and researchers from the fields of medical entomology, human and animal health and ecology.

KEYWORDS

code of practice, early warning rapid response, Integrated Vector Management, invasive, mosquito, Natura 2000, non-native, vector-borne disease surveillance

1 | INTRODUCTION

Wetlands provide essential resources to human societies such as water, food, building materials and livestock fodder (Gedan, Silliman, & Bertness, 2009). They can act as filters to pollutants, provide buffer zones against storms, sequester carbon and offer a wide range of cultural services (Barbier et al., 2011). Wetlands and their associated biodiversity have an estimated value ranging from US $44,597 to 195,478 per hectare per year (Clarkson, Ausseil, & Gerbeaux, 2013; Russi, 2013). Governments around the world have enacted legislation, policies and regulations including the Clean Water Act (United States) and the Water Act (Australia) to protect wetlands from a variety of human activities. In Europe, many wetlands and species are now protected through the Natura 2000 network, which extends over 18% of the EU's land area and almost 9.5% of its marine territory.

Several other European Directives aim directly or indirectly at improving the quality of wetlands, such as the Water Framework Directive (20/60/EC), the Urban Wastewater Treatment Directive (91/271/EEC) and the Nitrate Directive (91/676/EEC; European Commission). Despite these policies, wetlands with a designated protected status continue to face impacts from numerous ongoing and emerging threats indicating the need for further integration of water policies within different sectors related to agriculture, urban development, waste water treatment, climate and energy (Carvalho et al., 2019), public health and vector-borne disease mitigation (Medlock & Leach, 2015).

At the local level, managing wetlands can be challenging particularly when interventions interact antagonistically and lead to trade-offs between biodiversity conservation and public health. One of the problems often encountered around wetlands is the risk for mosquito-borne diseases or mosquito nuisance. Wetlands are natural breeding habitats for mosquitoes and this can create conflicts with human interests (Dale & Knight, 2008). Mosquitoes can pose a threat to public health as vectors of a wide range of pathogens and parasites. Mosquito-transmitted protozoa (e.g. malaria parasites such as *Plasmodium* spp.), metazoa (e.g. filarial worms) and viruses (e.g. dengue virus, Rift Valley fever virus and West Nile virus) are responsible for some of the most important mosquito-borne diseases (Tolle, 2009) and inflammatory and allergic reactions to mosquito bites are also common. Mosquitoes can also have adverse health impacts on wildlife especially wild birds, horses, livestock, cattle and pets (Martinez-de la Puente et al., 2015; 2016).

In the past, mosquito anti-malaria campaigns had negative environmental impacts as they relied on the draining of marshes and the use of chemical compounds such as the organochlorine pesticide DDT (Deonier & Gilbert, 1950; Rowlett, Weathers, Morrison, & White, 2016). In addition to chemical compounds, subsequent releases of non-native biocontrol agents such as the mosquito fish *Gambusia* spp., which were thought to be environmentally benign, have also impacted negatively on biodiversity (Pyke, 2008; Rupp, 1996).

Wetland mosquitoes can have an impact on human well-being and aesthetic services with social, cultural and economic implications by limiting outdoor activities that drive the tourism industry and local economies (Westerberg, Lifran, & Olsen, 2010). The control approaches for wetland mosquitoes will differ from the control approaches for mosquitoes found in urban areas such as the invasive species *Aedes albopictus* mostly breed in artificial containers. Fogging and residual insecticide applications (even though not recommended as control methods for invasive mosquitoes) are quite commonly deployed in urban areas when nuisance levels are high, mostly due to pressure from local communities and authorities or when there is a disease risk (high number of vectors and disease records in the area). Urban development, agricultural activities and leisure in close proximity to wetlands can induce changes in mosquito population dynamics and mosquito management activities and increase pressure for chemical control (Martinou & Roy, 2018). Unlike invasive mosquitoes, wetland mosquitoes inhabit important natural and biodiverse habitats. So, the only recommended method for their control should be the use of non-chemical larvicides; use of any chemical products should be prohibited within wetlands. A range of activities that contribute to the overall management of mosquitoes such as water drainage, chemical pesticide applications, planting of non-native trees and releases of non-native biocontrol agents have the potential to have adverse impacts on the environment and non-target organisms (Pescott et al., 2018). Knowledge about the role of wetland ecology and biodiversity in regulating wetland mosquito populations is often lacking from mosquito control programmes (Dale & Knight, 2008; Rey et al., 2012). In turn, wetland creation, conservation or restoration projects often ignore possible impacts posed by mosquito population dynamics, mosquito-borne pathogens, nor do they always include mosquito management plans (Willott, 2004). This hinders the ability of wetland managers and other stakeholders to deal with wetland mosquito populations in an effective and ecologically sound manner while ensuring wetland protection (Rey et al., 2012).

Mosquito management within an individual wetland may result from disparate policies and priorities of local, regional or national authorities, as well as public or private control agencies that are following recommendations of international organisations (The World Health Organisation, the Centres for Disease Control and Prevention, the European Centre for Disease Prevention and Control, the European Mosquito Control Association). European Regulation 528/2012 concerning the use of biocidal products stresses the importance of using products that are non-toxic to aquatic life. However, detailed guidance, to support the implementation of the Regulation, on alternative strategies that can be used for mosquito control, including in urban sites neighbouring wetlands, is lacking. There are currently no clear guidelines on what a mosquito control programme designed for wetlands should entail. A code of practice with guidelines or criteria for managing mosquitoes in European wetlands, that can help to guide stakeholders in reconciling priorities and decisions for sensitive sites depending on the local context, is urgently needed.

2 | MATERIALS AND METHODS

Sixteen international experts in vector management, medical entomology, parasitology and ecology met in Cyprus on 18 and 19 of April 2018 during a 2-day workshop on the management of native and non-native insect vectors of pathogens that affect human and animal health. The invited experts outlined the mosquito surveillance and control methods that are employed in various European wetlands: Cyprus, France, Greece, Spain, Sweden, Switzerland and the United Kingdom. This was followed by an interactive session during which all experts discussed and agreed upon a set of criteria, that in their experience, ensure the success of a mosquito management programme in wetlands while minimizing environmental harm. Topics that were discussed were: the area-wide approaches where the responsibility for mosquito control programmes is shared among different stakeholders; the need for training of pest control personnel in mosquito surveillance and management techniques as well as wetland ecology; the need for expertise in mosquito identification and monitoring, education and raising awareness regarding native and non-native mosquitoes at the local level; funding availability and allocation to wetland managers or local environmental health agencies for surveillance; designation of buffer zones free of urban development, chemical and habitat interventions; availability of environmentally sustainable control methods and the critical research gaps for understanding the effectiveness and environmental impacts of mosquito management.

3 | RESULTS

The proposed code of practice for the management of mosquitoes in wetlands across Europe consists of a set of nine criteria (Table 1). Local stakeholders can examine and elaborate on these criteria to apply them to the specific needs of their wetland of interest.

In general, a code of practice should entail guidelines that function independently of environmental changes (Figure 1). The proposed code of practice aims at recommending mosquito management strategies with no or minimal adverse environmental impact and provide guidance under different scenarios. Four scenarios are classified based on the societal problems caused by mosquitoes (Table 2).

Where there is minimal or no nuisance (scenario 1), i.e. there are no signs of complaints or discomfort by wetland visitors or local residents, we recommend the establishment of a passive monitoring

TABLE 1 Main criteria agreed as necessary to develop and deliver the framework for a successful code of practice

Criteria and explanations[a]
1. Assess the site and the scale of the mosquito burden
Consider which of the four different case scenarios are relevant: minimal or no impact of mosquitoes, significant nuisance, disease risk, non-native species introduction
2. Create site-specific mosquito inventories
The inventory should include the following information for each species at each of the problematic sites: Preferred breeding sites, vector-borne disease risk or nuisance, exophilic or endophilic activity, flight range and adult foraging patterns. This is a crucial step for an effective mosquito management plan and expertise in medical entomology is essential
3. Identify and engage stakeholders
Decision makers and public groups affected by mosquitoes can have an impact on the mosquito management plan. Communication with stakeholders at all steps is essential and will ensure an area-wide approach based on IVM principles and enable sustainability
4. Define the aim of the mosquito management plan
Co-develop a plan after consulting with other stakeholders with specifications on the desired outcomes and levels of control. Consider the feasibility and sustainability of the proposed measures so that negative environmental and non-target species impacts are minimal. The plan should include an internal and external operational assessment and quality assurance and control
5. Provide training for mosquito control personnel
Training should be specific and designed based on the desired outcomes of the mosquito management plan and the characteristics of the site of interest, ensuring health and safety and good practice
6. Design the overall strategy based on IVM principles
Essential components are the larval surveillance, mapping breeding habitats, adult surveillance, designation of buffer zones, habitat management, source reduction, available biological control, available chemical control options according to Biocides Regulations and resistance management. Assessment of the effectiveness of the chosen strategy. Monitoring effects of the management plan on non-target species
7. Create a sound recording scheme and database system
Collect georeferenced data during passive (community based-citizen science approaches) and active (adult trapping methods, larval collections) mosquito surveillance by mosquito control agencies, and data on abiotic conditions
8. Engage with the public
Share responsibility for mosquito control programmes with all relevant stakeholders, provide educational programmes, raise awareness and outreach regarding mosquitoes and your mosquito management plan. Establish a citizen-science surveillance system. Establish a surveillance system for non-native mosquitoes
9. Encourage research
On pesticide resistance, identification of native biocontrol agents, vector-borne disease monitoring and pathogen screening, effectiveness of different control strategies

[a]Securing funding was seen as a pre-requisite for essential resources that will enable data recording, the creation of repositories, purchases of equipment, training and outreach and the recruitment of personnel including environmental health technicians, entomologists, public health experts, pest controllers but is not listed as an explicit criterion in Table 1.

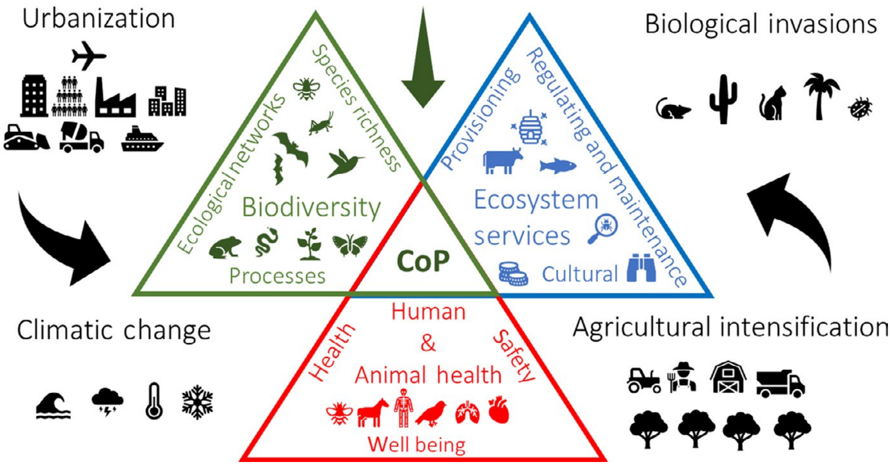

FIGURE 1 Proposed code of practice. Guidelines for effective mosquito management in wetlands while safeguarding human and animal health, biodiversity, and the provision of ecosystem services despite prevailing environmental change and external pressures on the wetland environment such as urbanization, agricultural intensification, biological invasions and climatic change

TABLE 2 Principles of the code of practice and the proposed available options under different case scenarios

Code of practice principles Know your site and scale of mosquito problem	Options	Scenario 1 Minimal or no mosquito nuisance	Scenario 2 Significant mosquito nuisance	Scenario 3 Disease risk due to native or invasive mosquito	Scenario 4 Introduction of invasive mosquitoes
Define aims and desired outcomes of management plan	Population monitoring	✓	✓	✓	✓
	Population suppression		✓	✓	
	Reduce contact rates with people		✓	✓	
	Elimination				✓
Design a strategy based on IVM principles	Mosquito inventory	✓	✓	✓	✓
	Passive surveillance	✓	✓		✓
	Active surveillance		✓	✓	✓
	Mapping of breeding sites		✓	✓	
	Data recording and management		✓	✓	✓
	Designation of buffer zones		✓	✓	
	Habitat management & source reduction		✓	✓	✓
	Biological control		✓	✓	✓
	Mechanical control		✓	✓	
	Chemical control			✓	✓
	Personal protection		✓	✓	
	Pathogen screening		✓	✓	
Identify research gaps and encourage research community	e.g. habitat requirements and anthropophily, contact rates with people, trophic interactions of non-native and invasive species with native species, resistance studies, biocontrol, environmental impact assements; effects of environmental change on mosquito species richness and abundance; effects of control measures on non-target species				

system based on citizen-science initiatives noting that mosquito records collated through smart phone apps or social media could be used (Palmer et al., 2017; Tyson et al., 2018). The potential of citizen science to inform invasive non-native species strategies and management has been widely demonstrated (Roy et al., 2015). While it is recognized that some taxa and environments present challenges for citizen science, there are many ways in which these can be overcome particularly through combining professional and volunteer surveillance approaches (Pocock, Roy, Fox, Ellis, & Botham, 2017). Provided that a system for taxonomic identification of citizen records by experts can be set up, passive surveillance could generate large datasets in an affordable manner that could not otherwise be collected during mosquito control programmes. Thus, surveillance by citizen-scientists may substantially reduce the costs associated with field work in active surveillance programmes. Resources could therefore be concentrated on active surveillance at mosquito hotspots (Kampen et al., 2015), e.g. within wetland sites where larval densities are high or at points of entry like ports and airports where invasive non-native mosquitoes could be introduced and spread. Costs related to running a passive surveillance scheme and developing a suitable application and platform for data recording, validation and management should be considered.

Where there is severe nuisance, frequent complaints and discomfort reported by wetland visitors and local residents (scenario 2), passive and active surveillance systems are necessary as well as a mosquito management programme that will ensure mosquito population reduction, especially for wetland sites that are in close proximity to urbanized areas. These programmes should rely solely on larvicidal treatments with biocontrol products such as bacteria, *Bacillus thuringiensis israelensis* (Bti). The use of alternative native biocontrol agents such as native fish e.g. *Aphanius fasciatus* in the Mediterranean should also be considered and supported by basic research on population dynamics and trophic interactions. *Gambusia holbrooki* and *Gambusia affinis* fish were released at multiple locations in wetlands around Europe but as these species are non-native to Europe and they are highly invasive further release is not recommended and populations of these fish should be eliminated where possible (Ruiz-Navarro, Verdiell-Cubedo, Torralva, & Oliva-Paterna, 2013).

When there is a risk of disease associated with native or non-native mosquitoes (scenario 3), e.g. West Nile Virus. Pathogen transmission tends to occur within the distribution of its competent vectors. It should be noted that the presence of a known vector species in a wetland does not necessarily mean that a disease can establish and cause harm. The vector needs to have sufficient abundance (as adults) and high contact rates with susceptible hosts and be able to replicate the causal agent and survive to transmit the infection to new hosts as set out in the vectorial capacity and basic reproduction number frameworks. More importantly the source of infection also needs to be present or introduced into the area. If potential vectors are confirmed to be present but at low abundance, remote from sources of infection, control should solely rely on larvicidal biocontrol agents such as Bti. When there are reports of any clinical cases of mosquito-borne diseases in sites near wetlands, or an infected host is introduced nearby and the potential vectors are present and active, then chemical adulticiding (e.g. pyrethroids) could also be considered as an emergency public health measure at urban sites but it should not be used within the wetland and natural sites as pyrethroids are toxic to aquatic organisms and can kill beneficial insects such as bees (Maund et al., 2012). Personal protection measures as well as netting around houses and bed nets should also be used by citizens inhabiting sites near wetlands or when visiting wetlands.

Where there is an introduction of invasive non-native mosquitoes (scenario 4), if alien species such as *A. albopictus* or *Aedes aegypti* are identified at an early stage of introduction within an urban location in close proximity to a wetland, chemical control could be considered, as for scenario 3. In that case chemical control should be considered only locally within the urban sites in combination with active surveillance, biocontrol methods and mechanical trapping.

4 | DISCUSSION

Integrated mosquito management (IVM) should be based on an Integrated Vector Management strategy that is area-wide and allows the optimal use of resources for vector control and improve efficacy and cost-effectiveness (Figure 2). It does not only require the adoption of different management actions but also the in-depth knowledge of the ecosystem and the interactions between mosquitoes and their natural enemies and also any pathogens.

The area-wide approach for managing insects as highly mobile as wetland mosquitoes requires adopting different approaches, including innovative tools such as drones for larvicidal applications within delimited areas to ensure co-ordinated and co-operative management through the efforts of different stakeholders, who will be prepared to share the successes or the failures of the IVM programme. The success of such area-wide programmes will depend on public

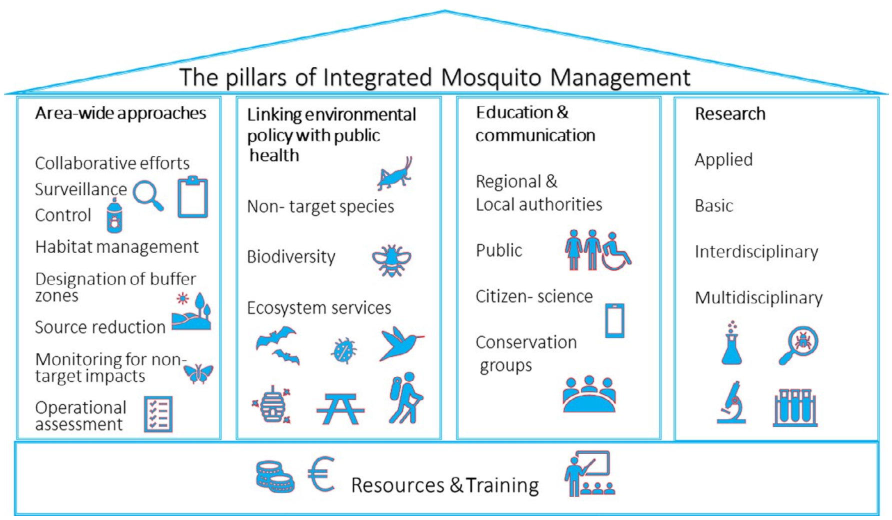

FIGURE 2 Pillars for an Integrated Vector Management strategy

participation and all stakeholders taking 'responsibility' of the mosquito problem.

It is important that there are provisions for active surveillance, data recording and management, as well as a good practice in mosquito control operations that will ensure human and environmental safety. Habitat management and source reduction (Figure 2; Table 2) refer to the limited manipulation of wetlands in particular circumstances to reduce their capacity for mosquito breeding, e.g. when artificial breeding sites are created within wetlands due to illegal dumping and waste disposal and not to the natural wetland per se. Degraded wetland habitats where mosquitoes are present in large numbers should be restored and rehabilitated as this could help towards reducing mosquito numbers. Emphasis should be placed on enhancing ecological processes and predator populations that help maintain the mosquito numbers within acceptable limits, and on understanding the impacts of control regimes on trophic interactions, both identified through basic and applied research. Ditching and runnelling are two techniques that have been used in the Australian continent and the Americas (Rey et al., 2012), where tidal sources drive the water in and out of marshy areas, however, these techniques are not applicable to non-tidal wetlands in Europe.

Mechanical trapping based on commercially available traps can be used to reduce the abundance of nuisance mosquitoes at a local scale. Although such mass trapping devices are expensive, which may affect their deployment at high density over large areas for control efforts, it is considered that their value in focal population reduction overrides this cost (Jackson et al., 2012).

Buffer or barrier zones, i.e. areas including and surrounding wetlands in which no human interventions and urban planning are carried out have been traditionally designated based on minimizing nuisance to breeding wetland bird species, mammals, and reptiles. However, as many mosquito species native to wetland habitats can disperse over different ranges, e.g. *Culex pipiens* fly between 0.16 and 1.98 km and *Aedes caspius*, up to 12 km, it is wise to include mosquitoes within environmental impact assessments for urban planning for sites in proximity to wetlands or during wetland restoration projects when assigning buffer zones (Ciota et al., 2012; Sudarić Bogojević, Merdić, & Bogdanović, 2011).

Mosquito flight capacity can be influenced by landscape structure, meteorological conditions (temperature, humidity and illumination), and species physiology (energy available for flight; Verdonschot & Besse-Lototskaya, 2014). Thus, the designation of buffer zones around mosquito breeding sites should be made based on mosquito and host density and human nuisance perception. The usefulness of a buffer zone will depend strongly on the mosquito species present at each location, this is why it is of immense importance to have mosquito inventories at the local level (Verdonschot & Besse-Lototskaya, 2014). In case there is also chemical control in urbanized sites surrounding a wetland, a buffer—free of chemicals—zone should be predefined especially since pyrethroids such as deltamethrin are toxic to aquatic life. Any chemicals considered for use in urban sites in proximity to wetlands should be previously licensed/authorized products designated for mosquito control and available to authorized mosquito control agencies. There should be clear guidelines provided by the mosquito control programme on application rates, surfaces and sites that can be treated and the size (width and length) of the buffer zone surrounding the wetland where chemicals will not be applied in order to protect wildlife as well as an insecticide resistance management plan.

Currently mosquito control practices across Europe differ. In Northern European countries, like Sweden, several permissions need to be sought from the environment agency, County Board and land owners before mosquito control agencies can be authorized to apply Bti, the most environmentally benign product targeting mosquito species. In other European countries, due to political pressures, synthetic pyrethroids might be used against nuisance species in urban areas neighbouring wetlands. In Mediterranean countries, including Cyprus, there is a more liberal approach to the use of synthetic chemicals where the local communities surrounding protected wetlands such as the Akrotiri salt lake use synthetic pyrethroids for mosquito control. While there is a plantation forest adjacent to the Akrotiri wetland, which could act as a buffer-chemical free-zone (Pescott et al., 2018), protecting the aquatic environment, there is considerable pressure from the local communities to apply pyrethroids in that buffer zone adjoining the Ramsar wetland site. Interpreting, adopting and implementing the nine criteria set within this code of practice for mosquito control programmes at the local scale will enable a balance between costs and benefits and it will help us maximize the benefits to human health while minimizing negative impacts on wetland ecosystem health (Hendrichs, Kenmore, Robinson, & Vreysen, 2007). This code of practice provides practical, advice to local authorities and individuals responsible for mosquito control in order to design an integrated mosquito management strategy in wetlands that align with current environmental legislation. Although it was developed by European experts, this holistic approach is transferable to other geographical contexts, integrating the expertise and knowledge of local stakeholders and researchers.

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AUTHORS' CONTRIBUTIONS

A.F.M. initiated and led the workshop and writing of the manuscript. All authors contributed to discussions during the workshop and contributed critically to the conception, design and drafting of the article.

DATA AVAILABILITY STATEMENT

Data have not been archived because this article does not use data.

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