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Wetlands and mosquito control in the twenty-first century

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Abstract This synthesis is a short introduction to the Wetlands and Mosquito Control special issue of Wetlands Ecology and Management. The geographic extent of the articles in this Special Issue comprises four continents (America, Asia, Australia, and Europe) indicating a global interest in the issue of wetland ecology and mosquito control. The unifying theme across these diverse papers is the increasingly close collaboration between ecologists, mosquito control, and regulators. Continuing anthropogenic effects on the wetland habitat and demand for mosquito control call for close cooperation between environmental and mosquito control communities. The new generation of wetland managers and mosquito control practitioners understands and accepts the common and compatible goals of preserving the remaining wetlands while addressing the public health concerns. This special issue is dedicated to Bill Walton (1956–2020) who was the driving force behind this endeavor. His career and research illustrate the close relationship between mosquito control and wetland ecology showcasing on how integrating wetland restoration, sustainable mosquito control efforts, and the social and cultural values of the communities will be crucial for the success of wetland management and mosquito control in the twenty-first century.

Keywords Mosquito control · Wetlands management

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Background

A decade has passed since the Special Issue on Wetlands and Human Health edited by Pat Dale and Roxanne Connelly was published in *Wetlands Ecology and Management* (Dale and Connelly 2012). These collected works proved very influential in validating and providing further impetus for interdisciplinary partnerships between wetland ecologists and mosquito control professionals. Ensuing rapid advances in our knowledge and valuation of wetland ecosystems, new approaches to mosquito control, and changing regulations, especially in the face of continuing anthropogenic effects on the environment, motivated the current update on the latest developments in the field. This Special Issue on Mosquito Control and Wetland Management presents current mosquito control practices in wetlands and frames them in historical, regulatory, and environmental contexts. These contexts are as important as the actual restoration and control methodologies because the current practices are strongly impacted by the anthropogenic changes in wetland habitat and by the constraints imposed by the regulatory agencies.

Mosquito control is rooted in the principle of integrated management, whereby rational science-based knowledge is used for cost-effective and sustainable vector control (Beier et al. 2008). Mosquito control is predicated upon a feedback loop of evidence-based decision making that takes into consideration: (1) mosquito vector and pathogen monitoring, (2) collaboration with land managers, policy makers and community, (3) public engagement, and (4) control methodologies that include chemical applications, biological control, and physical adaptations of the wetland habitat. Physical alterations of the wetlands were heavily leveraged during the early years of mosquito control before the development of biological and chemical technologies. Like so many other endeavors, mosquito control in the first half of the twentieth century was managed by engineers, resulting in drainage and extensive ditching of coastal and freshwater wetlands in many parts of the world (Bourn and Cottam 1950; Gedan et al. 2009; Nyman 2021). The development and introduction of synthetic pesticides such as DDT during World War II ushered in the next era of reliance on these "wonder" products. The indiscriminate application of these persistent pesticides in agriculture, forestry, household use, and mosquito control resulted in bioaccumulation in wetlands and widespread ecological impacts (Woodwell et al. 1971; EPA 1975; Herman and Bulger 1979). Rachel Carson's "Silent Spring" published in 1962 was the turning point in the nascent environmental protection movement followed by creation of a strict regulatory regime for pesticide products. Technological advances that produced non-persistent and biological pesticides spurred conceptual advances, such as integrated pest management (IPM), were enthusiastically adopted for mosquito control (Axtell 1979; Ehler 2006).

Compared to the recent past, the present-day practitioners of mosquito control have much more environmentally benign tools in their hands. However, the legacy problems stemming from the previous decades of indiscriminate ditching and pesticide applications remain and are addressed by several papers in this Special Issue. New problems have arisen with increased anthropogenic impacts on wetlands. Globally, wetlands have shrunk by 87% due to land conversion and urbanization over the last 300 years (Davidson 2014). Sea-level rise threatens many remaining coastal wetlands (Gedan et al. 2009; Kirwan and Megonigal 2013; Murray et al. 2014). Other threats are posed by invasive species, particularly those that outcompete and displace the native wetland vegetation (Houlahan and Findlay 2004; Bart et al. 2006; Ren et al. 2021). Wetland habitat loss on this scale has stimulated a public interest to preserve what remains and restore some of what was lost. Accelerated development abutting many wetland areas brings the populace increasingly closer to the sources of mosquito production and creates more need for effective mosquito control in freshwater or salt water habitats, and in urban and rural environments alike as illustrated in this Special Issue.

We would be remiss if we did not credit Dr. William Walton who conceived of and organized this Special Issue. His unexpected and untimely death was a shock to the scientific community. Dr. Walton's career exemplified the many facets of mosquito control and none more so than its close relationship with wetland ecology and management. He was a leading voice and a driving force in wetland mosquito management research, and we hope that his vision for this Special Issue, which is dedicated to his memory, has come into focus to benefit us all. We thank Eric Wolanski, the Editor in Chief of *Wetlands Ecology and Management*, for his unwavering guidance during the transition period, and all of the authors for their contributions and perseverance.

Overview of studies in wetlands and mosquito control special issue

This Special Issue is dedicated to the memory of William Walton; hence, the introductory article highlights each of his academic contributions. The full article is provided in the supplementary material and has the most comprehensive body of Dr. Walton's work—136 peer-reviewed references. The remainder of the studies in this Special Issue can be broadly categorized into those focused on constructed or agricultural wetlands and those in the natural wetlands (Table 1). These studies are briefly summarized below.

Table 1 Overview of the articles in the special issue

Article	Wetland type	Area	Control method	Purpose	Scale
Tribute to William Walton					
Metzger	Constructed and Managed	USA	All	Review of scientific articles authored by William Walton	Local to National
Constructed/agricultural wetlands					
McKay et al.	Stormwater	Illinois, USA	Physical	Assess impacts of cattail management on mosquito development and abundance	Local
Wheeler et al.	Rice fields	California, USA	Adulticide, biological, larvicide & physical	Review of mosquito control in rice fields	Local
Zhao and Xue	Rice fields	China	Biological, larvicide & physical	Review of mosquito control in rice fields	National
Managed natural wetlands					
Brochmeyer et al.	Mangrove wetlands	Florida, USA	Physical	Historical review of mangrove wetlands management on the east coast of Florida	Local
Castillo et al.	Tidal salt marsh	California, USA	Physical	Regulations that affect mosquito control activities from the ground and via drone	Local
Dale et al.	Tidal salt marsh	Queensland, Australia	Physical	Impacts of runneling on ecohydrology and mosquito control	Regional
Maher et al.	Tidal salt marsh	Northeastern USA	Physical	Multidiciplinary and cross-institution collaborative learning to improve saltmarsh restoration	Regional
Poulin et al.	Delta wetlands, lagoons, lakes, salt marsh	Provence Alpes-Côte d'Azur, France	Larvicide & physical	Impacts of mosquito control on wetlands birds	Local
Qualls et al.	Mangrove swamp and salt marsh	Florida, USA	Physical	Effects of mangrove expansion on *Aedes taeniorhynchus* abundance	Local
Smith et al.	Salt marsh	Northeastern USA	Physical	Vegetation loss due to waffle pools formed by water circulation channels	Regional
Wolfe et al.	Salt marsh	Northeastern and mid-Atlantic USA	Physical	Review of Integrated Marsh Management for controlling salt marsh mosquitoes	Regional

Tribute to William Walton

The career of Dr. William E. (Bill) Walton (1956–2020) is reviewed by Mark Metzger, a former graduate student from Bill's lab that is currently a Public Health Biologist with the Vector-Borne Disease Section of California Department of Public Health. Mark walks us through Bill's career from his beginnings at University of Rhode Island where he studied the life history of freshwater copepods through to his research on the efficacy of larvicides against *Aedes aegypti* mosquitoes in bromeliad plants at the University of California, Riverside. This review shows the arc of Bill's career across a wide range of disciplines, from the basic to applied sciences, illustrating the cross- disciplinary nature of mosquito control research and its overlap with aquatic ecology and wetland science.

Constructed wetlands

Constructed wetlands are typically considered as those made to treat wastewater or to mitigate for the loss of natural habitat. Rice production also relies upon constructed infrastructure to contain the water need to grow this semiaquatic crop. Constructed wetlands typically require routine physical maintenance to persist and the water entering them is driven by human activities and not by natural environmental factors. Mosquito control efforts in these habitats must be aligned with agricultural production, seasonal transitions from rice production to other uses such as bird habitat, and the intermittent flow of wastewater into the wetlands.

The contribution from McKay et al. offered insights into how vegetation management around stormwater drainage infrastructure affects oviposition rates and larva survivorship on *Culex* mosquitoes. The results supported the value of directing leaf clippings away from stormwater drainage and of encouraging the colonization of cattails over turfgrass around stormwater retention infrastructure.

Wheeler et al. provided an overview of a mosquito control program in the northern Central Valley of California, USA. Rice is a major agricultural commodity for the region, and rice fields occupy considerable land area there, making it fiscally infeasible to apply insecticides to all properties. Integrated Pest Management Program described in the articles utilizes the surveillance of mosquito abundance to focus mosquito control efforts where they are needed most urgently. Challenges for mosquito control in this area were discussed, including (1) dual purpose land use for rice agriculture and wetland habitat for waterfowl, (2) control product selection based upon the location of organic relative to conventional rice fields, and (3) mosquito cost-sharing with landowners. The latter is of high interest as it provides a financial incentive that encourages landowners to flood their rice fields post-harvest when temperatures are cooler and mosquitoes are less likely to reproduce in high numbers.

The paper from Zhao and Xue reviewed mosquito control practices in rice fields in China, a country where rice is a major domestic and export product. The study highlighted how mosquito control practices had changed from the 1950's to the present day and the impact these practices had on malaria. The wet irrigation technique, which involves periodic drying of the fields, had the positive impacts of conserving water while reducing mosquito production. The authors noted that this practice was also of environmental conservation value in China where half of the country's water is used for rice production. Fish cultivation in constructed wetlands is widely used to reduce mosquito abundance (Kangmin 1988; Wu et al. 1991), and in China, a practice that originated as early as 220 BCE. Its widescale adoption delivered not only mosquito control benefits, but allowed rice field farmers to harvest marketable fish providing additional economic benefits apart from public health and environmental improvements.

Managed natural wetlands

The managed natural wetlands that are considered in this Special Issue abut coastal habitats and consist of saltmarsh, mangrove forests, or estuary deltas with associated upland habitat. Mosquito abundance in these habitats has been of longstanding concern ever since people first began settling along the coast. Physical adaptations of the environment (e.g., water circulation channels) to limit the accumulation water that support mosquito growth and boost natural mosquito predators were the principal means of mosquito control until effective chemical-based control products were developed (e.g., larvicide and adulticide). The articles in this section highlighted the crucial need for a science-based and enduring management plan that is well funded, routinely assessed and revised based on environmental conditions, and considers the needs of people and wildlife alike. In the absence of such efforts, mosquito control is at peril of becoming less effective and the ecological benefits of a well-functioning wetland lost.

Brochmeyer et al. offered a historical review of mangrove wetlands management for mosquito control and development along the eastern coast of Florida (USA) from the late 1880s to the present. The early practices were harmful to many of the wetland ecosystem services. Recognizing this fact, wetland restoration efforts gained momentum during the late 1980s, motivating engagement among regulatory agencies, mosquito control programs, researchers, and communities. Restoration projects were also carefully monitored using science-driven metrics. The authors concluded that most of the restoration work countered prior anthropogenic damage, whereas the future projects will need to consider the impacts of the global climate change.

Regulators and land managers are key contributors to defining mosquito control and marsh restoration activities. Castillo et al. untangled the alphabet soup of regulatory agencies, management plans, and permit requirements that impact mosquito control work in tidal wetlands of California and more broadly across the USA. As unmanned aerial vehicles or drones (UAV) are being quickly adopted by mosquito control practitioners, this paper also reviewed the regulations that enable, and often limit, drone use in wetlands. A common theme throughout is a need for enhanced coordination among regulatory and permitting agencies in light of the new challenges and rapid environmental changes.

Dale et al. summarized 28 years of research on the impacts of runnels, shallow water circulation channels that are wider than their depth, on mosquito control and hydrology on the salt and mangrove marshes in Queensland, Australia. The study found a very considerable 29-fold reduction in larval mosquitoes at the runneled sites, while hydrology was unaffected suggesting negligible negative impacts on the environment. The value of long-term studies such as this became clear when after three years the authors found significant runnel erosion that self-healed as sediment accumulated over subsequent years. This study is expected to have a substantial impact as runnels are widely adopted as a restoration and mosquito control techniques elsewhere (Wolfe et al. 2021; Besterman et al. 2022).

Marsh restoration projects have the greatest potential for success when everyone that is involved or impacted are well informed and engaged. Maher et al. showed how this can be achieved with a collaborative learning exchange forum that engaged people of diverse professional backgrounds (academics, resource managers, environmentalists) in the planning stage for restoration and mosquito control projects. Positive outcomes included cross-discipline exposure, improved designs, streamlined permitting, and long-term professional engagement among participants. The collaborative approach can be adopted as a demonstrated improvement over the more typical single-agency model.

Government-sponsored mosquito control often occurs over large areas utilizing mechanization to disburse insecticides or manage the landscape. Poulin et al. cautioned that such intense activities can have unintended consequences that impacted waterfowl abundance at their study site in France. The study supported the critical importance of considering marsh ecosystems in a holistic manner that balances community needs for mosquito control with the wellbeing of wildlife and habitat protection.

The spatial distribution of many mosquito species is strongly impacted by climate, hydrology and wetland vegetation. Quals et al. investigated how environmental factors affected the spatial distribution of *Aedes taeniorhynchus* (Wiedemann), an aggressive biting salt marsh mosquito, over a 16-year period in Florida, USA. The study demonstrated that *Ae. taeniorhynchus* migrated to occupy newly restored salt and mangrove marshes, pointing to the importance of considering unintended consequences of restoration such as increased mosquito production, and to motivate advanced planning for the impacts these projects may have on mosquitoes.

Smith et al. characterized a new threat termed "waffle pooling" to salt marshes in eastern US that was facilitated by the combined effects of the legacy grid ditch network and sea-level rise. The authors quantified the effects of "waffle pooling" on salt marsh degradation and proposed management approaches to mitigate these negative impacts to restore native marsh vegetation and to increase marsh resilience to sea-level rise while controlling mosquito populations.

Wolfe et al. reviewed how landscape management practices for mosquito control in eastern US salt marshes had evolved during the last century, and how these practices may be adapted for climate change. The authors advocated for an integrated marsh management approach that incorporates all aspects of mosquito control in marsh habitats (physical, biological and chemical) with habitat preservation or restoration. The authors encouraged long-term monitoring at restoration sites and to develop plans in advance with land managers that incorporate multiple stakeholder perspectives.

Synthesis

The geographic extent of the articles in this Special Issue comprises 4 continents (America, Asia, Australia, and Europe) indicating a global interest in the issue of wetland ecology and mosquito control. Most of the studies were conducted in tidal wetlands along the coasts. This was not by chance. More than 40% of the world's population inhabits the coastal areas, which account for just 4% of the land surface (Gedan et al. 2009). Moreover, the human populations and urbanization in coastal areas have been increasing at a much faster rate than inland, and this trend is expected to continue in the foreseeable future resulting in the highest population densities in the world along the coasts (Neumann et al. 2015). This proximity of highly urbanized and tidal wetland environment brings about public health and ecological consequences. It places human populations near mosquito vector and biting pest habitat. Pathogens transmitted by salt marsh or mangrove mosquitoes include malaria, Venezuelan Equine Encephalitis virus, and California encephalitis group (Grimstad 1994; Osorio and Yuill 1994; Russell 2002; Becker et al. 2003), with many of the salt water *Aedes* species that are also important biting pests globally. Tropical estuaries can harbor *Vibrio cholera* (Batabyal et al. 2014), which may enter the water column as water circulation improves (Wolanski and Elliott 2015), initially increasing the risk of disease as restored wetlands begin to regain their natural function. Urbanization and population growth have also led to widespread tidal wetland destruction and degradation (Gedan et al. 2009; Kirwan and Megonigal 2013; Murray et al. 2014). These trends of imperiled wetland habitat and continuing demand for mosquito control call for close cooperation between environmental and mosquito control communities. The new generation of wetland managers and mosquito control practitioners understands and accepts the common and compatible goals of preserving the remaining wetlands while addressing the public health concerns (Rochlin et al. 2012). Increasingly, we work in close collaboration, pooling our limited resources and further underscoring the need to enhance communication and exchange information and ideas across disciplines. Integrating wetland preservation and restoration, the economics and sustainability of mosquito control efforts, and the social and cultural values of the communities will be crucial for the success of wetland management and mosquito control in the twenty-first century.

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