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Engaging urban stakeholders in the sustainable management of arthropod pests

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Abstract

The management of arthropods in urban environments is complex. Although there are species that threaten human health and property, there are also extensive communities of beneficial species that need to be conserved. Current management of arthropod pests in cities relies heavily on the use of synthetic chemicals, which have a range of potential environmental and health impacts. In order to mitigate the impacts of insecticides, urban stakeholders need to be encouraged to reduce reliance on chemical control and adopt more ecologically sustainable approaches. Integrated Pest Management (IPM) has been globally successful in managing pests in agriculture but has yet to be broadly practiced in urban systems. Here, we address the global problem of lack of IPM uptake in urban areas. We summarise current arthropod management practices, with comparisons drawn between the management of pests in urban and agricultural systems, and highlight the benefits of IPM. We then give examples of successful IPM to demonstrate the useful implementation strategies and identify key barriers to the adoption of this approach in urban systems. In particular, the high diversity of stakeholder interests and management practices is a key barrier to overcome in cities, along with lack of awareness of the benefits and implementation strategies of IPM, little emphasis on monitoring pests, restrictions in time/resources; and social factors such as negative public perceptions of insects and policy regulations. We offer suggestions for overcoming these barriers in the hope of encouraging greater application of sustainable arthropod pest management practices for all urban stakeholders.

Keywords

Integrated pest management, urbanisation, arthropod, management, community

Key Message

- Despite extensive benefits, integrated pest management (IPM) has had little uptake in urban areas.
- Barriers include limited integration between disciplines and regulatory bodies, a lack of knowledge of urban pest ecology, and diverse stakeholder interests.
- Overcoming these barriers requires: comprehensive monitoring systems; IPM compatible tools; support for commercial operators to be agents for change; and the development of support networks for all stakeholders.
- Adoption of IPM in cities will reduce environmental and public health impacts, redefine how residents relate to arthropods and encourage sustainable management of urban ecosystems.

Author Contribution Statement

E.L. conceived the idea and assembled all co-authors. E.L., T.L., C.W., M.W., and M.S. all contributed equally to formation of the outline and writing the content of this review.

1. Introduction

Building cities drastically modifies natural habitats, which adversely impacts arthropod communities and ultimately drives the localised extinction of many species (McKinney 2008). Some arthropods are able to adapt to these changes, leading to increases in abundance and, in some cases, the establishment of the species as a pest. A pest is an anthropocentric term, and simply means a disruptive plant or animal that causes annoyance or damage in a given context. In an agricultural system this primarily refers to organisms that damage crops, affect livestock health or stored product quality. In an urban setting, the main pests of concern are usually those that cause nuisance, present a human health risk through the transmission of pathogens, inflict structural damage and impact local plants (Robinson 1996). While the disservices associated with arthropod populations may require active management, strategic responses should also consider the ecosystem services provided by arthropods in the urban environment. There is also often a mismatch between the public perception of arthropods and the pest impacts they pose. This results in the use of insecticides to control arthropods that do not necessarily pose a substantial economic or public health threat (Shrewsbury and Leather 2012). For the purpose of our review, pests are organisms that have a direct economic impact on public health, urban vegetation or built structures, rather than arthropods that may simply be perceived by some people as a pest but cause no direct damage (New 2015).

Any arthropod species can become a pest in certain contexts, even perceived beneficial species, depending on their ecological characteristics. Arthropod pests typically arise when humans increase their proximity to pest species' habitats, where modification of the environment increases the numbers of a native species, or where a non-native species is introduced (New 2015). In cities, some arthropods adapt to, and thrive in, the newly created habitats (e.g. urban waterways, dwellings, waste) and once established, can cause damage to: structures, stored products, food production and both native and cultivated vegetation; as well as presenting significant health risks. The population dynamics of urban arthropod pests and their predators are influenced by a range of factors including land use (Burkman and Gardiner 2014, Nelson and Forbes 2014), climate (Meineke, Dunn et al. 2014) and biological community structure such as increases in prey or loss of predators (Faeth, Warren et al.

2005). Globalisation also increases the opportunities for exotic pest species to be introduced to new urban areas (Benedict, Levine et al. 2007).

Maintaining the function of global urban ecosystems is essential. To achieve effective management of these systems, urban stakeholders should adopt a preventative approach based on long-term investment and evidence-based decisions that reduce pest damage and public health risks while conserving the diversity of beneficial arthropods (New 2018). This will be a critical challenge with the trend of "greening cities" and the subsequent management of urban green spaces (Aronson, Lepczyk et al. 2017) and consideration will need to be given to how the beneficial and pest arthropods associated with these habitats are managed.

In order to encourage local authorities and the community to reduce their reliance on chemical control and increase uptake of sustainable arthropod pest management practices in urban areas, our study aims to a) give an overview of current management, b) explain Integrated Pest Management (IPM) and how it could be adapted for use in urban pest management practice c) provide examples of successful IPM strategies and outline strategies that could be used in urban areas, and d) describe the key barriers to uptake and changes in practice needed in order to implement IPM strategies in cities. This paper also identifies knowledge gaps and explores the need for partnerships between local communities, government, industry and research in order to address these problems.

2. Management of arthropods in cities

Urban pest control strategies are traditionally reactive and often locally-applied, rather than focused on long-term integrated management of pest arthropod populations (Knipling 1998; Varga 2017). This strategy is often prompted by the need for short-term control of arthropods posing a public health risk or immediate threat to property or vegetation. The diversity of habitat types and municipal systems in urban areas, as well as different resource requirements and life history of urban arthropod pests, makes broad scale management a challenge.

Since the 1940s the use of chemicals to control pests has increased in urban areas because it is considered cheap, easily accessible and effective (Dahlsten and Hall 1999; Grube et al. 2011). Household and municipal pest control is still dominated by high levels of pesticide use and while the reduction in pest arthropods of public health importance (e.g. mosquitoes) is of benefit, consideration should also be given to less positive outcomes of insecticide use in both the environment and community (Julien, Adamkiewicz et al. 2008). These include significant environmental impacts such as runoff into waterways (Amweg, Weston et al. 2006, Holmes, Anderson et al. 2008, Weston, Asbell et al. 2011, Wittmer, Scheidegger et al. 2011) and human health impacts ranging from developmental disorders to chronic health problems (Ma, Buffler et al. 2002, Rauh, Perera et al. 2012, Hernández, Parrón et al. 2013, Narayan, Liew et al. 2013). However, a balance is often required where the risk to human health of insecticides is exceeded by the risks posed by arthropods of medical importance (e.g. vectors of pathogens) (Peterson, Macedo et al. 2006). While the use of insecticides is regulated by government authorities in many parts of the world (Li and Jennings 2017), even where human health impacts may be low, there remains concern regarding the non-target impacts of broad-scale insecticide use and subsequent ecological impacts. These concerns, together with challenges posed by increasing rates of insecticide resistance in key pest species of public health concern (Deming et al. 2016), have driven research into alternative strategies of mosquito management. The release of laboratory reared mosquitoes either carrying pathogens that inhibit pathogen transmission (Hoffmann et al. 2011) or reproductive success (Rasic et al. 2014), or are genetically modified to drive reductions in local mosquito abundance (Carvalho et al. 2015) are strategies gaining increasing interest from local authorities. These approaches may substantially reduce the non-target impacts of broad spectrum insecticides but require substantial investment in community educations to gain support for such programs.

The desire among urban communities and government authorities for more ecological sustainable pest management is driving the need for new regulatory approaches and a shift towards IPM which uses complementary techniques to limit pest levels below a given threshold, rather than focusing on individual pest species (Coll and Wajnberg 2017). There is huge potential for the use of IPM to control arthropod pests in urban ecosystems (Olkowski, Olkowski et al. 1976, Sawyer and Casagrande 1983, Brodeur, Abram et al. 2017) and in the last 30 years there has been some evidence of success (Olkowski, Olkowski et al. 1978, Brewer and Stevens 1983, Wan, Cai et al. 2018) but limited translation into practice. The lack of widespread adoption is likely the result of a broad range of knowledge, social and environmental barriers for multiple stakeholders including tenants, landholders, community groups, local government, and businesses.

The primary benefit of using IPM approaches to manage arthropod pests in urban areas such as houses, businesses and green spaces is to reduce dependence on chemical control methods and reduce the subsequent threats to the environment and human health. Research in the 1980s showed that the amount of pesticides applied per area in urban gardens and lawns was higher than that used in agriculture (Dahlsten and Hall 1999). Yet the current extent of this phenomenon is unknown, because many countries do not keep pesticide use records (Voldner & Li 1995); in those that do, urban homeowners are rarely required to have a chemical application license, or to keep records of amounts used (e.g. Bekarian et al. 2006; The State of Victoria 2017). Many insecticides are broad spectrum, meaning that non-target arthropods, including beneficial species, are adversely affected. This can have significant impacts on ecosystem services and function (Chagnon, Kreutzweiser et al. 2015). The repeated use of the same insecticides has the additional risk of increasing resistance by pests to those insecticides (Naqqash, Gökçe et al. 2016). Resistance means that pest resurgences can become more common and more difficult to manage, resulting in increases in the application rate and concentration of insecticides in an effort to control the pests. The development of resistance results in the insecticide no longer able to control the pest, posing significant challenges where there is a reliance on insecticides to stop outbreaks of vector-borne disease (Deming, Manrique-Saide et al. 2016). Targeted and judicious use of insecticides is essential for resistance management, which lowers the rate of insecticide resistance and increases the sustainability of management of public health threats (Endersby-Harshman, Wuliandari et al. 2017).

IPM can be more effective at controlling pests than non-integrated strategies, such as managing pests in isolation or by using only broad-spectrum pesticides (Brenner, Markowitz et al. 2003, Miller and Meek 2004) especially in high-density housing developments. Better land management can increase urban predators and decrease reliance on chemical control in urban agriculture (Wan, Cai et al. 2018). IPM strategies also have a number of flow-on benefits. For example, nursery sites for biological control agents (e.g. insect predators) such as conserved vegetation and habitat restoration, can benefit a variety of other species (Begg, Cook et al. 2017). In addition, highlighting the role that healthy ecosystems play in IPM could increase the social and economic value of urban wildlife and help to drive natural resource management policy. By educating members of local communities on pest management through biological control and encouraging them to adopt IPM strategies, there is the added benefit of increasing engagement with nature thereby positively influencing health (Bowler, Buyung-Ali et al. 2010) and creating a drive to develop sustainable cities. Ultimately, urban IPM requires a multidisciplinary approach with contributions from ecologists, social scientists, agricultural scientists, ecotoxicologists, public health officials, local government, strata management, natural resource managers, pest control operators and residents. Managing the expectations of so many stakeholders is one of the primary barriers to IPM in cities but the ecological and social benefits are invaluable.

3. Definition and types of IPM

IPM was originally developed because excessive use of broad spectrum insecticides had triggered resistance among pests (rendering the insecticides ineffective), environmental damage and public health concerns. In agriculture, IPM integrates a range of biological, cultural and chemical techniques to maintain pest numbers below their economic threshold (Stern et al. 1959; Kogan 1998, Wilson et al 2018). The economic threshold of a pest is that at which the pest starts to decrease the profitability of the crop. In this paper an urban pest is defined as having a monetary cost in terms of public health, spoilt food, or damaged property. Therefore, if the pest in an urban setting is below its economic threshold, no control is needed. The aim of IPM is not to eradicate pests, but to manage them.

Effective IPM incorporates three general aspects: management practices, monitoring, and decision-making (Kogan 1998; Barzman et al. 2015; Wilson, Whitehouse et al. 2018). 1) Management practices are in place to reduce the chance of pests exceeding their economic threshold and their need to be controlled; 2) Pest numbers are monitored to identify when they reach threshold; and 3) If the threshold is reached, decisions are made to select the control method which has the lowest toxicity and fewer adverse impacts. Preference is given to control methods that are highly specific to the pest targeted. If a pest is still above its threshold after the application of a control method, an alternative method may be selected by considering its potential impact on the targeted pest and the risk of adverse disruption to the ecosystem. Broad spectrum insecticides are more likely to have an adverse impact on the local ecosystem because of their effects on non-targeted beneficial or neutral organisms. Consequently, within IPM, broad-spectrum insecticides should be considered only when no other methods have worked.

Techniques used in IPM exist on a continuum from prevention using management techniques (those in place to stop pests reaching their economic threshold) through to intervention using pesticides (those used to control pests once they do reach the threshold; Figure 1.) Control methods to stop pests reaching an economic threshold include habitat manipulation to stop pests thriving (such as removing stagnant water to control mosquitoes (Dale, Knight et al. 2014)); and to increase the abundance of beneficial species (e.g. parasitoids, predators, pest-specific diseases or fungi, insectivorous birds). Pre-emptive control methods may include introducing exotic beneficial species to a region to control pest numbers (after appropriate assessment of the exotic species' potential non-target impacts (Davies, Carr et al. 2011). An effective IPM system is one where pests are well monitored, and rarely reach their threshold, with minimal disruption to ecosystem function.

If pests exceed their threshold, the methods used for control range from biological, biopesticides, through to selective and broad-spectrum chemical insecticides. The softest option is augmented biological control, where a key beneficial organism is released to attack pests (van Lenteren 2012). This approach tends to work best in stable environments such as greenhouses, or perennial crops (Stern et al. 1959; Chambers, Wright et al. 1993, Gerson and Weintraub 2012). Among the biopesticides, semiochemicals alter pest behaviour rendering them less destructive (Dicke and Sabelis 1988, Cook, Khan et al. 2007) and microbial biopesticides contain a virus or bacterium, which attack the target pest, e.g. Nuclear Polyhedrosis Virus used to control caterpillars (Washburn, Trudeau et al. 2003). Chemical insecticides range from those highly selective and targeted with low toxicity to vertebrates, to broad spectrum chemicals, such as organochlorines and organophosphates, which are highly toxic to most arthropods and vertebrates. An example of a targeted insecticide is pyriproxyfen, a growth regulator that targets insect larvae by stopping them from developing into a mature insect.

Although good selective tools are vital in an IPM program, equally important are the pest monitoring techniques. To be effective, an IPM system needs monitoring methods that are easy to undertake, coupled with clear economic thresholds and a clear understanding of what can influence these thresholds. Additionally, a support information network for the pest controllers is vital, so that the controller can have confidence in the decisions they make. In summary, the success of an IPM program depends on the pest control tools available, the dedication of the pest controllers, the accuracy of the monitoring methods, and the ability of social networks to provide unbiased support to the pest controllers.

4. Comparison of pest management in urban and agricultural systems

In urban environments the primary land uses that require arthropod management are houses and businesses, green spaces such as parks and gardens (including water bodies), and urban agriculture spaces and nurseries. There are fundamental biotic, abiotic, and social differences between these urban land uses and agricultural systems that affect arthropod pests and their management. These differences must be recognised in order to successfully apply IPM strategies in urban areas.

4.1 Biotic

Most agricultural IPM strategies focus on monoculture systems, where one or a few plant species are grown in high density. In contrast, urban environments tend to have higher plant species richness (Wania, Kühn et al. 2006, McKinney 2008), including a large proportion of exotic species. Since much of urban land is privately owned and managed, socioeconomic variables can strongly influence biotic diversity. For example, a study in Phoenix (USA) found higher plant diversity in wealthier regions (Hope, Gries et al. 2003), while a study in Chicago (USA) found that cultural diversity positively correlated with plant species richness. That is, ethnically mixed neighbourhoods had greater species richness than ethnically homogeneous neighbourhoods (Lowenstein and Minor 2016).

Urban areas are characterised by extreme levels of habitat heterogeneity as many different land uses and planting strategies can occur over relatively short spatial scales. As a consequence, species turnover (beta diversity) tends to be relatively high in urban areas, with big variation in species composition between adjacent but differentially managed properties (Rebele 1994, Niemelä 1999, Wania, Kühn et al. 2006, Aronson, Handel et al. 2015). The high species turnover found in urban areas could pose unique challenges for urban IPM because pest species are less concentrated thus hindering attempts to use low-dispersal biological control agents such as mites or small parasitoid species. High heterogeneity and a big proportion of privately owned (and potentially inaccessible) land also makes monitoring more difficult than in traditional agricultural environments. However, studies have demonstrated that where urban agriculture is undertaken in cities, it contributes to increased biodiversity that may provide crucial ecosystem services such as pollination and pest control (Lin, Philpott et al. 2015). Rather than a challenge, the diversity of arthropod habitats in cities may offer benefits not yet fully appreciated.

The composition of arthropod communities differs significantly between urban and agricultural landscapes (McIntyre, Rango et al. 2001). In Arizona (USA) arthropod predators, herbivores and detritivores were more abundant in agricultural sites than in urban ones, but omnivores enjoyed equal abundance across all site types (McIntyre, Rango et al. 2001). Urbanisation affects trophic dynamics by shifting control of food web dynamics. A study in the Phoenix area (USA) found that control of arthropods shifted from bottom up, resource based control in natural environments to top-down control from birds in urban areas (Faeth, Warren et al. 2005). Human activities result in a large influx of food waste including resources such as high sugar and high protein foods that are naturally difficult to obtain. The large amounts of food waste generated by urban environments is a boon to omnivores, particularly those with a large diet breadth. For example, Penick, Savage et al. (2015) found that a significant proportion of urban ants' diets were obtained from 'human foods'.

4.2 Abiotic

The modification of soil structure and vegetation composition in agricultural systems results in significant changes to the abiotic environment. These changes are even more extreme in urban landscapes that are characterised by large areas of impervious surfaces such as bricks, pavement and asphalt, in addition to the removal of shrubs and dead wood (Marzluff and Ewing 2001). Up to 80% of land in central urban areas is covered by pavement or brick (Blair and Launer 1997). The high concentration of impervious surfaces can lead to the ‘heat island effect’, which can cause urban areas to be as much as 12 degrees C higher than surrounding areas (Imhoff, Zhang et al. 2010). These abiotic changes are likely to impact pest communities in cities. In Raleigh, North Carolina (USA), higher urban temperatures were correlated with increased abundance of herbivorous arthropods, but not with abundance of spiders; indeed, spider taxa known to control herbivorous arthropods were absent from the hottest sites (Meineke, Holmquist et al. 2017). This decoupling of predator-prey dynamics can cause a loss of top-down control. Heavy metal contamination in urban soils can also have a negative impact on natural enemies resulting in shorter life spans, slowed development and reduced reproduction (Gardiner and Harwood 2017).

Urban waterways also have the potential to represent important pest insect populations because mosquito species that are highly tolerant of polluted waterbodies are able to thrive (Kassim, Webb et al. 2013). Without the presence of local aquatic predators or competitors more suited to less polluted habitats, urban wetlands can be a source of mosquitoes (and other flying insects) that may be nuisance pests or public health risks (Russell 1999).

4.3 Social

In agricultural systems, the stakeholders are primarily producers, who have similar goals in regards to pest control and land management. In comparison, the complexity and diversity of stakeholders in cities can make urban IPM particularly challenging. Cities contain a multitude of stakeholders often with radically divergent views on how urban animals should be managed. For example, urban beekeeping (of European honey bees, *Apis mellifera* L.) is being increasingly adopted by individuals wanting to contribute to bee conservation efforts; yet the species is introduced in many parts of the world and increasing urban beekeeping efforts may have numerous social and ecological impacts (Colla and MacIvor 2016). An organic community garden, a preschool, a restaurant and a private garden may have entirely different philosophies about pest management. The threshold level before chemical control begins will also differ substantially between individuals, and convincing stakeholders to accept non-zero thresholds may be difficult. For example, Vetter and Hedges (2018) point out that homeowners would likely call a pest controller if a single venomous brown recluse spider was observed in their home, despite the fact that the threshold for the safe number of brown recluses is set at 6 spiders per house (Vetter and Hedges 2018). Since much of urban land is privately owned and managed, landscape level IPM programs require the cooperation and coordination of many independent home and business owners**.**

5. Examples of successful strategies using IPM to control arthropod pests

IPM in urban settings involves broad and complex issues and multiple types of pests, for example horticultural, medical and household (Raupp et al. 2010; Fonseca et al. 2013). To understand some of these complex issues it can be useful to compare examples of successful implementations in different contexts.. The two case studies below of IPM in an agricultural (Australian cotton production systems) and an urban setting (mosquito control) demonstrate how different environmental and social challenges can be overcome in order to implement programs that are successful over long time periods. We include an agricultural example because most knowledge of IPM success comes from agricultural systems and this knowledge is essential to inform the design and adoption of urban IPM programs. These two examples also highlight the breadth of social, economic and ecological issues involved in IPM problems.

5.1 Pest control in Australian cotton

In 1999 the Australian cotton industry changed from trying to eradicate pests, to adopting an IPM approach. The change was triggered by resistance by key pests to broad spectrum insecticides. In the heavy pest season of 1998/99, broad spectrum insecticides were unable to control these pests, rendering cotton production unprofitable, nearly collapsing the industry and triggering change. Consequently, in 1999, it was the growers themselves instigating the move towards IPM (Wilson, Whitehouse et al. 2018).

Aiding the uptake of IPM was the extensive IPM toolkit that had been developed over the decades prior to 1999, during periods when resistance rendered insecticides ineffective (Wilson, Whitehouse et al. 2018). The tools included 1) cultural techniques, such as plant compensation (Hearn and Room 1979), 2) enhancing the activity of “beneficials” (e.g. predators, parasitoids, or diseases, Mensah 2002) and identifying the economic thresholds for key pests (Whitehouse 2011); 3) mechanical techniques including cultivating to destroy pests (Fitt and Forrester 1987); 4) targeted insecticides such as spinosad (Wilson, Whitehouse et al. 2018)) and 5) effective biopesticides (Gould, Anderson et al. 1991). Transgenic “Bt” cotton, which in its current form is cotton that has been genetically modified to produce three proteins toxic to the key lepidopteran pests *Helicoverpa* spp, was first introduced in 1996. Bt cotton, which is supported by a comprehensive Resistance Management Plan, has been a corner stone of IPM in cotton since 1999 (Torres, Ruberson et al. 2010, Whitehouse, Wilson et al. 2014). Since 1999, insecticide use in cotton has dropped from about 30 insecticide sprays per season, to around 3 (Wilson et al 2018) illustrating the positive effect of cotton IPM.

Another important factor in the success of IPM in cotton has been the large support network providing information to growers (the controllers in an IPM program, Figure.2). The network includes industry extension officers, which distribute information from the researchers to the growers and consultants. Growers are also supported by consultants (funded directly by the grower) who provide information on pest management and agronomy. This network was developed through an industry wide extension program which included field days, workshops, and the development of networks to enable growers to discuss IPM issues and co-ordinate pest management activities across a region. Researchers working with growers also demonstrated the profitability of an IPM approach (e.g. (Whitehouse 2011)) providing growers with more confidence to use IPM methods.

Key to the success of IPM in cotton, and in other agricultural systems (Bottrell and Schoenly 2018), is that it was grower driven, there was an extensive and varied IPM toolkit that was effective, and a large and flexible support network that not only provided information and advice to growers but support within the grower community.

5.2 Mosquito control in urban areas

Mosquito-borne disease has been a growing concern for health authorities across Australia for many decades. In recent years, the pest and public health risks associated with mosquitoes in urban areas have increased as new residential and recreational areas encroach on existing mosquito habitats and the construction and rehabilitation of wetlands enhanced conditions for mosquitoes within metropolitan regions (Claflin and Webb 2017, Crocker, Maute et al. 2017). This increased exposure has brought with it an increased risk of endemic mosquito-borne diseases, including the most common mosquito-borne disease in Australia, Ross River virus (approximately 5,000 cases reported annually; (Claflin and Webb 2015)). In addition, there is the threat of container-inhabiting mosquitoes (i.e. mosquitoes adapted to exotic water-holding containers around houses) associated with the transmission of dengue viruses (DENV). The container-inhabiting mosquitoes have required local authorities to broaden their focus from local wetland habitats to suburban backyards (Webb and Doggett 2016).

Mosquito management by authorities in urban settings has followed an IPM approach, both historically and contemporarily. Key to success has been a diverse IPM toolkit including the use of mosquito control agents, habitat management, community education and consideration of emerging technologies. For example, historically, mosquito control in urban areas of Australia used a range of techniques, focusing on modifying habitats, applying control agents (e.g. petroleum oils, organochlorines, organophosphates) or releasing invasive fish (e.g. the plague minnow, *Gambusia holbrooki*) (Webb and Joss 1997, Pyke 2008). However, although these techniques were diverse, they were not very selective.

In recent decades, a more ecologically sustainable approach to mosquito control is in place, underpinned by monitoring programs of mosquitoes and research identifying mosquito habitats, the environmental conditions that drive mosquito abundance, and the activity of mosquito-borne pathogens. Modern mosquito control primarily involves the use of more selective mosquito control agents (i.e. minimal non-target and negligible human health impacts) than the previously employed insecticides (e.g. organochlorides, organophosphates), including insect growth regulators (*s*-methoprene); biopesticides (*Bacillus thuringiensis israelensis* (Bti)) and is complemented by appropriate habitat modification (Russell and Kay 2008).

Mosquito IPM is constantly evolving from a social perspective. First, there are two dominant types of mosquitoes: wetland mosquitoes and container-inhabiting mosquitoes. Management of these two types needs to occur at two different community levels: either by local authorities (in the case of wetland mosquitoes) or by householders (container-inhabiting mosquitoes). Therefore, successful mosquito IPM of these mosquitoes will look quite different. In addition, concern about mosquitoes is also divided between the local authorities and householder levels. Household impetus to control mosquitoes will vary between regions depending on their perceived risk, irrespective of whether the mosquitoes originate from wetlands or containers. Therefore, the community involved in managing the mosquitoes (either the authorities or household) may be different from the community concerned about their control (which again could be either the authorities or household).

IPM can be used both by authorities to manage wetland mosquitoes, and by households to reduce container-inhabiting mosquitoes. Local authorities must co-ordinate management approaches and acknowledge that mosquitoes and their habitats do not adhere to government boundaries. This approach enables local governments to share resources in managing local mosquito risks, including public health messaging that educate the community on personal protection measures (e.g. behavioural change; the safe and effective use insect repellents; (Webb 2015, Webb and Hess 2016). Better multiagency coordination will further remove barriers to effective mosquito management (Dale, Knight et al. 2014).

Management of container-inhabiting mosquitoes is essential in order to reduce local outbreaks of disease for example DENV, which is triggered when infected travellers are bitten by local *Aedes aegypti*. This mosquito is closely associated with water-holding habitats found in backyards. In central and far north Queensland, Australia, a program integrating surveillance of mosquito populations and human disease, targeted insecticide use, education of the community, and employment of emerging technologies, has greatly reduced the burden of disease within the region. As pest management had to occur at the household level, local authorities educated householders (increasing their perceived risk) by continually running awareness and education programs. These encouraged householders to minimise potential mosquito habitats within their properties and enact targeted mosquito control around properties of infected individuals. As householders play an important role in reducing the availability and suitability of water-holding containers for *Ae. aegypti* (Kolopack, Parsons et al. 2015), the strong community engagement and education strategies have been critical to the success of the mosquito control program in this region.

5.3 Comparison of successful IPM case studies

Despite their differences, the examples of successful IPM in cotton pest management and mosquito control reveal strong similarities. In both situations, there is an extensive toolkit ranging from habitat modification, to targeted or broad-spectrum chemicals. In addition, even though tolerance thresholds of pests were quite different, the use of control methods in both situations were based on monitoring for pest or disease outbreaks. Key in both systems is the social aspect. First, the implementers of IPM were mobilized either through a crisis (cotton growers) or through education (householders). Second, there was a strong network of services supporting the controllers (Figure 2), in the form of industry groups (cotton) or local authorities (mosquito management). Consequently, IPM can be effective in most situations, provided controllers are motivated, a large range of management techniques are available, good monitoring methods are established, and there is strong community support.

6. IPM strategies for different interest groups in urban areas

There are a number of IPM tools that have the potential to be successful in urban areas (Figure 1) but the large and diverse stakeholder contingent is one of the most challenging aspects of implementing IPM in cities. Urban stakeholders have different goals, values, resources and concerns; to be effective, an IPM strategy must therefore be tailored toward the target stakeholder group (Schoelitsz, Poortvliet et al. 2018). For example, cockroaches are a nuisance pest for both home and restaurant owners, but for restaurants, the presence of even low cockroach numbers can violate health regulations and incur associated fines. In contrast, the economic consequences of a low-level cockroach infestation in a private dwelling are substantially lower. Thus, while both restaurants and home owners would do well to focus on behavioural changes to avoid cockroaches (such as ensuring all food is sealed, emptying bins before night fall and locating and sealing potential cockroach harbourages) home owners, to whom the economic impact is less, can wait longer before escalating to chemical control.

Alternatively, restaurant owners may need to implement chemical control alongside behavioural changes.

Different stakeholders operate at very different scales and in different locations. Homeowners, for example, are generally working at the relatively small scale of a privately owned dwelling while a city council will need to work at the landscape scale. IPM strategies also need to be adapted to either the indoor or outdoor environment. Biological control agents will be less desirable for stakeholders treating indoor spaces, while insecticidal baits are best applied indoors where they are less likely to have non-target impacts. Indoor pest management entails treatment in an enclosed space and thus caution must be used when selecting aerosol insecticides. IPM approaches to indoor pest arthropods, such as cockroaches, can reduce the use of pyrethroid insecticides while still achieving satisfactory reductions in pest arthropod abundance (Zha, Wang et al. 2018).

While different stakeholder groups require different IPM solutions (Figure 1b), there can be tremendous within-group variation. Hope, Gries et al. (2003) found that wealthier city-dwellers lived in neighbourhoods with higher plant diversity; this in turn could mean a more robust guild of predator and parasitoids and better natural pest control. In the United States, people living in poor neighbourhoods are more likely to report the presence of cockroaches, yet this is the demographic with the least access to quality pest control services and the highest rates of cockroach-sensitive allergic asthma (Olmedo, Goldstein et al. 2011, Camacho-Rivera, Kawachi et al. 2014, Do, Zhao et al. 2016).

Beyond pest control within residential dwellings, there may be distinctly different attitudes to reduced insecticide use and adoption of an IPM approach, depending on an individual’s or community group’s attitudes. For example, those with an interest in improving urban biodiversity conservation (Dearborn and Kark 2010) may have different motivations that lead to variability in their IPM approach. A growing interest in IPM within a community may be fostered through strategies to conserve arthropod populations, particularly pollinators (Hall, Camilo et al. 2017). Here IPM can play a critical role facilitating community engagement with biodiversity conservation in cities.

7. Overcoming barriers to the adoption of IPM in urban areas

Many of the challenges involved in improving adoption of urban IPM are similar to those involved in encouraging effective invertebrate conservation strategies (Cardoso, Erwin et al. 2011, New 2018). Investment in long-term education and training strategies is essential to achieve a shift toward more sustainable urban pest control strategies. This is a difficult task due to significant scientific, social and regulatory obstacles that need to be overcome before effective IPM standards can be established for urban pest control. In this section we outline a number of tools and initiatives that can be applied by all stakeholders in order to overcome these barriers (summarised in Figure 2).

7.1 Lack of scientific knowledge

Scientific knowledge of many invertebrate fauna is severely limited, with large knowledge gaps in taxonomy, ecology and life histories of most species (Cardoso, Erwin et al. 2011). This information is critical to designing effective IPM strategies, especially involving natural enemies, or where introduced pests establish in new regions. In addition, effective IPM should take a holistic multi-pest approach, yet a lot of IPM research in agricultural systems has traditionally focused on individual species (Horne, Page et al. 2008), with limited understanding of interactions between multiple arthropod taxa because of their complexity (Costamagna 2009), or how pest management impacts non-target species like pollinators (Biddinger and Rajotte 2015).

Designing evidence-based urban IPM programs requires long-term investment in a broad range of research, beyond just the life histories and ecology of particular pest species. Urban systems foster unique dynamics and interactions compared to agricultural or natural systems. Therefore, existing knowledge of pest species in agricultural or natural systems may prove irrelevant in urban systems. Yet arthropod communities in urban areas have been studied far less than birds and mammals (Magle, Hunt et al. 2012). There is ample scope for more research to understand how multiple factors influence pest populations and their management in urban areas. For example, the effects of urban warming or climate change on pests (e.g. (Meineke, Dunn et al. 2013, Dale and Frank 2014)), how municipal insecticide use influences pest populations and their natural enemies (e.g. (Szczepaniec, Creary et al. 2011)), the relative importance of top-down and bottom-up effects on herbivorous pests (Raupp, Shrewsbury et al. 2010), and the effect of numerous other complex factors like pollution and traffic, fragmentation, mowing regimes, vacant land and more (Jones and Leather 2012, Gardiner, Burkman et al. 2013). Much of the urban arthropod literature has focused on pest taxa, with relatively limited knowledge of beneficial species, including predatory and parasitic arthropods and pollinating species. Conservation biological control, a key tool in IPM programs, is one of the most understudied ecosystem services in urban systems (Ziter 2016). Greater understanding of how urban landscape management can enhance natural enemy populations is essential to develop effective IPM strategies.

7.2 Cultural and economic factors

Research on understanding the barriers to the adoption of IPM is dominated by work in agricultural systems, with limited knowledge of social barriers to IPM adoption in urban areas. Effective IPM is knowledge-intensive and insufficient knowledge or training, lack of technical support and costs to the farmer are some of the key reasons cited for failure to adopt IPM programs on farms (Horne, Page et al. 2008, Parsa, Morse et al. 2014). Factors such as cost also influence IPM adoption in urban systems (Miller and Meek 2004, Paine, Millar et al. 2015); however, subjective human factors, like aesthetics, health, comfort, are likely to be more important drivers of IPM adoption in urban settings compared to agriculture (Sawyer and Casagrande 1983). For example, a study of professional landscapers in the United States found that customer demand for ‘the perfect lawn’ was one of the primary barriers to IPM adoption (Ingram, Stier et al. 2008). Media representation is also an important driver of people’s attitude toward particular arthropods, even if they have limited personal experience with those taxa (Sammet, Andres et al. 2015). Encouraging accurate media representation of arthropod behaviour and ecology is critical to increasing public understanding, and this can be easily addressed via scientists taking on public engagement and science communication roles in popular and social media (Smith and Saunders 2016; Berenbaum 2017).

Individual attitudes to arthropods are a key underlying factor in social acceptance of urban IPM. Not only will an individual’s attitudes vary, independent of actual or potential perceived pest impacts (New 2015) but these attitudes are likely to vary greatly within and between communities engaged with the implementation of IPM. Negative human attitudes to arthropods, particularly insects and arachnids, are widespread and well-documented in the literature (Byrne, Carpenter et al. 1984, Prokop, Tolarovičová et al. 2010, Last 2014) and are likely a fundamental driver of pest control attitudes. For many people that fear or loathe arthropods, using pesticides regularly to kill unwanted arthropods takes less effort and has immediate results compared to manual removal or investment in biological control tools that may take longer to have an effect. These negative attitudes are not changed quickly, and require comprehensive, long-term education and engagement programs (Last 2014). For example, the Master Gardener programs in North America have enabled participants to develop their scientific knowledge of natural systems, including their understanding of insects and the differences between pest and beneficial species (Schrock et al. 2000; Dirks and Orvis 2005).

In some instances, short-term responses by local authorities are required where an invasion by exotic arthropods could increase the risk to public health, or cause significant damage to property or vegetation. While in these instances control following IPM principles may not be desirable, or even possible, to implement, the outbreaks can highlight that a benefit of long-term IPM is a reduced reliance on insecticides. A study from California, USA, found that residents gave social and financial support to manage arthropod pests of urban street trees using biological control rather than applying insecticides (Jetter and Paine 2004). This was echoed in another study on street tree management in California where the biological control of arthropod pests damaging trees held substantial economic returns (Paine, Millar et al. 2015).

In agricultural systems, Farmer Field Schools have been successful in building ecological knowledge and improving the uptake of IPM among farmers, with numerous positive social, economic and environmental outcomes (Van den Berg and Jiggins 2007, Yorobe, Rejesus et al. 2011). Farmer Field Schools have predominantly operated in Global South countries, providing on-the-job training for farmers who use their own farms to trial the knowledge they learn with peer and expert support. A similar model can be developed for urban communities. In particular, community gardens can be an important tool in the long-term education and changing attitudes of urban communities. These gardens provide spaces for creating social-ecological memories within the communities, and building local traditional knowledge that transcend generations and personal networks (Barthel, Folke et al. 2010). For landscape scale effectiveness of biological control tools, collective and coordinated neighbourhood action is essential to avoid the process being disrupted, e.g. by pesticide use (Paine, Millar et al. 1997), and community education programs can achieve this (Olkowski, Olkowski et al. 1976).

Incentives for urban individuals to adopt IPM may also be somewhat different to incentives in farming systems. For farmers, customer demand or increased market prices for environmentally sustainable produce can be an important reason for adopting IPM (Mzoughi 2011). Customer/client preferences may well influence the adoption of IPM in urban food industries, but individual urban dwellers do not have the same incentive to reduce pesticide use to please others. There is an urgent need for research into what influences understanding and adoption of IPM in urban systems, to inform effective education programs. For example, Mzoughi (2011) found that 'doing the right thing' was an even more important driver of a farmer's decision to adopt IPM than cutting production costs, and education programs that tap into human ethical or environmental concerns may prove effective at enhancing IPM adoption in urban environments. As the community has increasingly adopted energy-efficient and water-efficient strategies in cities (Dieu-Hang, Grafton et al. 2017), so too may come the uptake of IPM to manage arthropod pests.

7.3 Management and community

Although good selective tools are vital in an IPM program, equally important are how those tools are managed through the pest monitoring techniques. As the experience in agricultural settings has shown, an effective IPM system needs monitoring methods that are easy to undertake, coupled with a good understanding of the pest economic thresholds and what can influence these thresholds. Key to the uptake of tools and their sustained use is the community in which IPM is undertaken. Controllers need a trustworthy information network that quickly provides them with information on new techniques and improved understanding of the pests and their thresholds, so that controllers can have confidence in the decisions they make. In some urban contexts, commercial applicators may be more trusted than scientific experts or government officials (Rickard 2011), so they need support and incentives to act as agents for change in urban systems.

Unfortunately, in many agricultural systems support networks are built by chemical and seed distributors which have a vested financial interest. An independent, trusted network is important for an effective IPM program to develop and be sustained (Bottrell and Schoenly 2018). An IPM program requires the controller to have a much deeper understanding of the system with which they are working than an eradication program (Wilson, Whitehouse et al. 2018). Therefore, the controller needs the community support of similar like- minded colleagues with whom they can discuss challenges and remedies to give each other support in their decisions. In the cotton industry, this takes the form of Area Wide Management groups (Wilson, Whitehouse et al. 2018). Providing residents with this level of confidence would require a well-functioning information network and the community support of other like-minded residents. Such programs also exist in urban areas to manage pest arthropods. For example, in New Jersey, USA, area-wide IPM has been successful in reducing nuisance-biting impacts of mosquitoes as demonstrated by social and economic benefits where such programs exist (Shepard, Halasa et al. 2014).

Monitoring programs engaging citizen scientists, and crowd-sourced data, indicate how communities could be engaged to enhance IPM in urban settings and can be a useful tool for building public knowledge and behavioural change related to urban arthropod communities (e.g. (Jordan, Gray et al. 2011). For example, citizen science monitoring programs have been very successful in increasing public understanding of urban bird ecology (Brossard, Lewenstein et al. 2005, Celia, Eleanor et al. 2005), and this is a promising area of research and practice for educating about IPM and urban arthropod communities (e.g. (Paine, Millar et al. 1997). Such approaches can be adapted to monitor arthropod pests with citizen science and crowd-sourced data already providing information on invasive species in many regions (Hawthorne, Elmore et al. 2015, Maistrello, Dioli et al. 2016, Palmer, Oltra et al. 2017). An additional advantage of establishing networks of "citizen scientists" engaged in monitoring urban arthropod populations, is that it also provides the framework for effective provision of community education (Williams, Hawthorn-Jackson et al. 2017).

The community driven approach has also been used with some success in agricultural systems: The Queensland fruit fly (Qfly) monitoring program involved maintaining a trapping grid in orchards and peri-urban areas across key horticultural regions in southern Australia that provided surveillance outcomes and promoted community awareness (Sutherst, Collyer et al. 2000, Dominiak and Daniels

2012). There is also a precedent set by countries in the European Union such as Germany, France and the Netherlands who all have laws introduced to restrict or ban the use of chemical pesticides in urban green spaces (PAN 2009). IPM programs are extremely cost effective for urban landscape pest control, but they require a long-term coordinated effort from government bodies, universities and the public to maintain education, keep ahead of new pests, and integrate environmental and human health goals (Goodell, Zalom et al. 2014). The sense of being part of a community involved in a citizen science project gives people a sense of responsibility and ownership of the project. Such an approach could be adopted to develop an IPM program in an urban setting.

7.4 Policy and Regulation

The decision of individuals to adopt IPM at the household or community level is influenced by public policies. Indeed, public intervention to promote IPM is essential, to reduce the social and environmental side effects of pesticide-intensive pest management, such as environmental contamination and human health issues (Lefebvre, Langrell et al. 2015). Public intervention can also promote coordinated area-wide programs to reduce reservoir populations of nuisance social insects (Dimarco, Masciocchi et al. 2017). However, the success of these intervention programs also depends on communication, training and education programs. For example, some states in the United States of America have a law mandating IPM in schools. Yet Anderson (2015) found that not all schools implement IPM, some schools still rely on reactive pest control, and in some schools there was a lack of communication between facility managers and school administration. To enable IPM to be widely adopted and successful, local authorities need to actively raise awareness of the environmental and public health benefits of IPM and extend their involvement beyond education to economic and operational support.

Despite a long history in research and rearing of generalist natural enemies, there is still a frustratingly low uptake of augmented biological control by consumers. This is largely due to the dominance of cheap pesticides as an easier option, and the lack of regulatory incentive for adopting sustainable pest control (van Lenteren 2012). As discussed above, there are numerous ways that education programs can increase public awareness and access to more sustainable pest control methods. But knowledge of policy barriers to IPM in agriculture shows there are a variety of strategies to provide incentives for

IPM. These include changes to regulatory instruments that promote sustainable pest management practices, taxes on pesticide use, commitment to publicly-funded research on the benefits IPM has on urban communities, and improved information dissemination (Ramirez and Mumford 1995, Chandler, Bailey et al. 2011, Lefebvre, Langrell et al. 2015).

8. Conclusions

Adoption of IPM in urban areas would produce a broad range of benefits, including reductions in pesticide usage and conservation of biodiversity. In order to shift public and government practice we need to better express these benefits. There are a range of IPM tools that could be applied to urban pests, yet current levels of uptake have been limited by the complexity of the urban stakeholder market. In order to improve urban pest management, the first step is to develop support and information sharing networks that connect stakeholders and encourage good practice. There is a critical need for more research into urban arthropod ecology and management, particularly to build a better understanding of the environmental drivers of pest outbreaks and beneficial arthropod communities in urban areas. Addressing the knowledge gaps and improving management requires interdisciplinary support from a wide range of ecologists, biologists, economists and social scientists. In order to apply this knowledge and implement sustainable practice we also need to establish better connections between researchers, urban residents, natural resource managers, government bodies, and pest controllers.

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Figure Legends

Figure 1: Pyramid of IPM techniques (the tool kit) that are used in a) agricultural systems, b) individuals and managers in urban systems. The foundation of the pyramid is low toxicity prevention techniques (green) which progress to more invasive intervention techniques (red) (modified from https://www.epa.gov/managing-pests-schools/definition-verifiable-school-ipm)

Figure 2. Strategies and tools to aid the adoption of IPM by urban stakeholders. The stakeholders in IPM adoption in cities take on a number of roles (sometimes concurrently): Controllers, Monitors, Users, Educators, Suppliers and Regulators. While widespread adoption of IPM in cities faces a number of barriers, solutions to overcome these challenges exist (the IPM techniques), but rely on long-term coordinated collaborative efforts from research institutions, governments, businesses and residents. This figure demonstrates how IPM could adopted for each stakeholder group through the use of support (green), toolkits (red) and monitoring (yellow) techniques.