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Managing nuisance social insects in urban environments: an overview

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ABSTRACT
Urbanization is progressing worldwide where social insects often attain pest status. We present an overview of the practices applied for the management of social insects in urban settings from 1990 to 2016. We found that most studies focus on the management and/or control of the colony via chemical means, many approaches based on controlling individual workers have been tried with less success than colony-level treatments, and only few used an integrated pest management approach. Less common is undertaking the reduction of populations through the control of the worker caste, by taking advantage of the Allee effects. This is an approach that could be further explored for sustainable control of social insects.

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Introduction

Urban environments – human settlements with high population density and human-built infrastructure – are expanding worldwide, as a rapidly growing human population becomes progressively urbanized. While in the 1900s only 14% of the population lived in cities, by 2009 more people dwelled in cities than in rural areas. Moreover, it has been predicted that total global urban area will triple between 2000 and 2030 to accommodate a doubling in the human population (Secretariat of the Convention on Biological Diversity 2012; United Nations 2014).

For living organisms, urban environments can cause dramatic changes. Natural habitats for many species are completely eliminated or reduced in availability rendering them to local extinction. In turn, for some species, a variety of new environments can be created (Koenig et al. 2002; McKinney 2002). In some cases, the development of cities has shown to negatively affect whole plant and animal communities, while in other, some species (mostly non-native) are favoured by an enriched habitat of food and shelter, otherwise hard to find or non-existent in natural environments (Ditchkoff 2006; Sol et al. 2013).

It is widely known that human-aided transport is probably the most important component of the arrival and geographical spread of many invasive species. Given the large number of people in cities and the concentrated movement of the population travelling to and from urban conglomerates, the urban environments are highly exposed to increased propagule pressure by non-native species. Built-up settings may not only open-up new niches for plants and animals but may also lack the natural enemies that can regulate their populations, hence helping the establishment or population growth of exotic species (Suarez et al. 1998; Walker et al. 2009).

In the urban setting, social insects are often observed likely because they are especially able to take advantage of the new features offered by these novel environments (Rust & Su 2012). Also, it has been noted that often some social insects can be good invaders and rapidly achieve pest status, as nearly a quarter of the alien insect species reported to become pests and cause environmental problems in the invaded range, are eusocial (Beggs et al. 2011). Eusociality involves a variety of ecological and behavioural traits, such as overlapping generations and brood care cooperation that may contribute to the great ecological success of eusocial insects and allow them a rapid local adaptation (Wilson 1987; Robinson 1992; Sagili et al. 2011). Temporal polyethism (i.e. age-correlated patterns of task performance) common in social insects, allows young workers to perform tasks within the nest and older outside which let them enhance ecological success by exposing older individuals to the most dangerous tasks (Robinson 1992).

In the arthropods, sociality has evolved in the Hymenoptera (some wasps and bees and all ants), in all Isoptera (termites), in some Thysanoptera (albeit, only very few species), in the Hemiptera and in the marine sponge-dwelling shrimp (*Synalpheus regalis*) (Batra 1966; Wilson 1971; Duffy 1996). Although only 2% of all known insect species are known to be eusocial, they can become locally very abundant and are common to most land habitats (Silverman &

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Brightwell 2008). The biomass of ants alone, for example, constitutes more than half of that of all insects combined (Hölldobler & Wilson 1990).

Defining the pest status of an organism and the corresponding decisions to apply control measures in agricultural and forestry systems is primarily based on the economic losses caused by the pest to a given crop or plantation (Robinson 1996). However, for social insects and other arthropods in urban environments, this criterion seems partly inadequate. In some cases, the economic losses can be estimated; an example is the Formosan termite *Coptotermes formosanus*, which can cause structural damage in the Southern United States worth approximately 1 billion USD per year (Corn et al. 1999). Also, for some stinging insects, such as several species of ants, hornets and yellowjackets, the medical costs have been valued, allowing setting a baseline for their control (Pimentel et al. 2005; MacIntyre & Hellstrom 2015). Still, for most social insect pests in urban areas, the decision to apply management measures is based largely on the potential damage or injury they may cause or, more often, on human values such as comfort or cleanliness. This is because many of these organisms are generally unwanted or unwelcome in urban areas, whether their numbers are few or many (Robinson 1996). This is why for urban integrated pest management (IPM), a focal point of research and extension efforts is the human factor, besides the economic losses that the pest causes. Social scientists, including specialists in human perception and behaviour, environmental designers, urban planners among others, may be involved in the research of the management strategies to be implemented in urban IPM (Sawyer & Casagrande 1983).

An important aspect why social insects in urban environments warrant control, is when they threaten human life.The Hymenoptera stings are among the most important causes of systemic allergic reactions. Only in the USA, stings by this insect order are held responsible for 40 deaths per year (Casale & Burks 2014). Also, the Pharaoh ant in Korea and in the USA, for example, may cause bronchial asthma and thus become a problem especially in hospitals, since they have the potential to mechanically transmit pathogenic bacteria (Beatson 1972; Eichler 1990; Kim et al. 2007). Another example is the red imported fire ant *Solenopsis invicta*, for which many people (approximately 1% of the world population) can suffer severe allergenic responses to even a single sting (Stafford et al. 1989; Baluga et al. 1996; Porter 2000). These impacts on humans added to the fact that social insects can achieve high numbers, even in the urban setting, and are often alien species, partly explains why social insects are unwanted in urban environments and deserve attention from the pest management standpoint.

Despite the clear need for management, the control of social insect pests in the urban setting presents still many challenges. There is large variation in the biology of the pest species, differences in human dwelling conditions within urban areas and among regions or countries, and probably more importantly, a diversity of both the needs and approaches applied to manage social insect pests. With the aim of understanding the possible drivers of success in social insect control in urban environments, we assemble here the standing information on the management practices applied. In doing so, we attempt to highlight what are the promising research topics which may contribute to improve our abilities to manage populations of these noxious organisms. We also discuss a less common approach to undertake the reduction of populations through the control of the worker caste, by taking advantage of the Allee effects.

Management practices applied to social insect pests in the urban environment

Different strategies and approaches have been used to manage populations of social insects in urban habitats. Our aim was to gather relevant information to obtain an overview of the current strategies implemented for their control and management that may allow identifying the critical issues that lead to successful control and the promising topics to focus on in further research. This topic has been covered in detail in a previous review by Rust and Su (2012); but the primary objective there was to highlight those social behaviours that can be exploited to control social insect pests in urban environments with the minimal use of pesticides. A wide compilation of the published articles is shown in Table 1. We searched *Google Scholar*, *Scopus* and *Web of Science* databases, using the terms: 'social insect' + control + 'urban environment'; ant + control + 'urban environment'; wasp + control + 'urban environment'; termite + control + 'urban environment' and their plurals. The selected articles covered publications that study the use of chemical, non-chemical and IPM approaches between 1990 and 2016, with the exception of a few studies (n = 5) before the 1990s that were included because they were the only ones who have evaluated particular control strategies that have not been used after then.

A total of 153 studies were found, most of them focused on termite management strategies, followed by ants and wasps (43.9%, 32.5% and 23.5%, respectively, Table 1). We noted that most of these studies implemented colony-level treatments with the aim of reducing the population size. By colony-level treatment we refer to all treatments that are apply directly to the nest or could be transmitted among workers or from workers to reproductives, but ultimately killing the colony (for example: toxic baits) (Figure 1). In turn, individual-level treatment studies implemented strategies aimed to reduce the annoyances that individual

Table 1. Management practices for social insect pests in urban environment and their degree of success.

Control strategies	Group	Species	Strategy	Level treatment	Target species	Result	References
Attractants	Ants	*Linepithema humile*	Installation of artificial nests	C	SS	Successful	Enríquez et al. (2013)
		Linepithema humile	Trail pheromone disruption ((Z)−9-hexadecenal)	I	SS	Unclear	Greenberg and Klotz (2000); Suckling et al. (2008); Tanaka et al. (2009); Nishisue et al. (2010); Suckling et al. (2010)
Attractants	Wasps	Wasp species	Citrus soda	I	SS	Successful	Wegner and Jordan (2005)
		Vespula spp.	Octyl butyrate	I	DS	Successful	Davis et al. (1972)
		Vespula spp.	Synthetic organic attractants	I	DS	Unclear	Davis et al. (1967)
		Vespula germanica, V. pensylvanica	Acetic acid + different wasp attractants	I	SS	Unclear	Landolt (1998)
		Vespula vulgaris, V. germanica	Different wasp attractants	I	SS	Unclear	El-Sayed et al. (2009)
		Vespula spp.	Heptyl butyrate	I	DS	Unclear	Gulmahamad (2002); Rust et al. (2009); Rust and Su (2012)
		Wasp species	Isobutanol-acetic acid mixture	I	SS	Unclear	Wegner and Jordan (2005)
		Vespula germanica, V. pensylvanica, Polistes aurifer	19 wasp attractant + acetic acid + short branched alcohols	I	SS	Unclear	Landolt et al. (2000)
		Vespula vulgaris, V. germanica	7 synthetic wasp attractants	I	SS	Unclear	El-Sayed et al. (2009)
Attractants	Termites	*Cryptotermes brevis*	Light wavelengths (460–550 nm)	I	SS	Successful	Ferreira and Scheffrahn (2011); Ferreira et al. (2012)
Biological control	Ants	*Solenopsis invicta*	Ant-decapitating flies (*Pseudacteon*)	I	SS	Successful	van der Meer et al. (2007)
		Ant species	Fungal pathogens	C	DS	Unclear	Pereira and Stimac (1997)
		Solenopsis invicta	Microsporian (*Kneallhazia solenopsae*)	C	SS	Successful	Williams et al. (2001); Valles and Pereirs (2003); van der Meer et al. (2007)
Biological control	Termites	Termite species	Virus species	C	SS	Unsuccessful	Grace (1997)
		Termite species	Bacterial species	C	DS	Unclear	Grace (1997); Devi et al. (2007)
		Reticulitermes, Heterotermes, Kalotermes, Coptotermes	Different pathogen	C	DS	Unclear	Grace (1997)
		Termite species	Fungal pathogens species	C	DS	Unclear	Grace (1997); Woodrow and Grace (1998); Rath (2000);Delate et al. (1995); Milner (2003); Lenz (2005); Chouvenc et al. (2008); Jackson et al. (2010)
		Reticulitermes, Heterotermes, Kalotermes, Coptotermes	Different pathogen	C	DS	Unclear	Grace (1997)
		Heterotermes aureus	Nematodes	C	DS	Unclear	Woodrow and Grace (1998); Weeks and Baker (2004); Lenz (2005)
		Coptotermes formosanus	Termite-specific bacterium (*Trabulsiella odontotermitis*)	C	SS	Successful	Tikhe et al. (2016)
		Termite species	Predators: berothid larva, ant	I	DS	Unclear	Wells and Henderson (1993); Cornelius and Grace (1995, 1997); Grace (1997)
Biological control	Wasps	*Vespula* spp.	*Sphecophaga vesparum burra* and *S. orientalis*	C	SS	Unsuccessful	Beggs et al. (2002); Donovan et al. (2002)
		Vespula spp.	*Sphecophaga vesparum vesparum*	C	SS	Unsuccessful	Donovan et al. (1989)
		Vespula spp.	fungal pathogens (*Aspergillus flavus, Metarhizium anisopliae, Beauveria bassiana*)	C	DS	Unclear	Glare et al. (1996); Rose et al. (1999); Harris et al. (2000); Jackson et al. (2010)
		Vespula spp.	Nematode (*Steinernema carpocapsae*)	C	DS	Unclear	Moller et al. (1991); Gambino et al. (1992); Beggs et al. (2011)
IPM	Ants	*Linepithema humile*		C	SS	Successful	Ward et al. (2010); Rust and Su (2012)
		Lasius meglectus		C	SS	Successful	Rey and Espadaler (2004)
IPM	Termites	Termite species		C	DS	Successful	Anonymous (2007)
Nest treatments and fumigation	Ants	*Atta sexdens rubropilosa*	Lime stone	C	SS	Unsuccessful	Schoereder et al. (2012)
		Solenopsis invicta	Spot insecticide treatments	C	SS	Unclear	Collins and Callcott (1995)
Nest treatments and fumigation	Termites	Specific species	Fumigation with sulfuryl fluoride	C	SS	Successful	Lewis and Haverty (1996)
		Specific species	Cold	C	SS	Successful	Lewis and Haverty (1996); Verma et al. (2009)
		Cryptotermes brevis, Coptotermes formosanus, Reticulitermes speratus	Heat	C	SS	Successful	Lewis and Haverty (1996); Woodrow and Grace (1998)
		Specific species		C	SS	Successful	Rust and Su (2012)

(*continued*)

Table 1. (*Continued*)

Control strategies	Group	Species	Strategy	Level treatment	Target species	Result	References
			Nest injection of insecticides, as liquid, dust or foam				
		Incisitermes snyderi, Cryptotermes brevis	Disodium octaborate tetrahydrate (DOT), calcium arsenate and chlorpyrifos	C	SS	Unclear	Scheffrahn et al. (1997)
		Incisitermes minor	High voltage electricity	C	SS	Unclear	Lewis and Haverty (1996, 2001)
		Termite species	Chemical treatments	C	DS	Unclear	Milano and Fontes (2002)
		Subterranean termite species	Orange oil extract	C	DS	Successful	Raina et al. (2007)
		Vespula spp.	Cypermethrin	C	DS	Successful	Beggs et al. (2011)
Nest treatments and fumigation	Wasps	*Vespa* spp., *Vespula* spp., *Polistes* spp.	Pyrethrin or pyrethroid dust	C	DS	Successful	Beggs et al. (2011)
		Polistes dominula	Thiamethoxam spray or foams	C	SS	Successful	Roper (2010)
		Vespula germanica	Resmethrin spray	C	DS	Unclear	MacDonald et al. (1980)
Perimeter spray and barriers treatments	Ants	*Monomorium pharaonis*	Granular bait containing a contact insecticide (hydramethylnon)	I	SS	Unclear	Oi et al. (1996)
		Linepithema humile, Tapinoma sessile	Aromatic cedar mulch	I	SS	Successful	Meissner and Silverman (2001)
		Linepithema humile	Non-toxic physical barriers	I	SS	Successful	Meissner and Silverman (2003); Menke and Holway (2006); Silverman et al. (2006)
		Linepithema humile	Banding vines and trees with sticky or repellent materials (semiochemicals and related chemicals)	I	SS	Successful	Shorey et al. (1992); Shorey et al. (1996)
		Linepithema humile	Insecticidal power barriers	I	SS	Successful	Rust and Knight (1990)
		Linepithema humile	Insecticide sprays + an attractive pheromone ((Z)−9-hexadecenal)	I	SS	Successful	Choe et al. (2014)
		Linepithema humile	Trunk-injected dicrotophos to hemiptera reduce + liquid bait	I	SS	Successful	Brightwell et al. (2010)
		Linepithema humile	Fipronil	I	SS	Successful	Greenberg et al. (2003); Scharf et al. (2004); Klotz, Rust, et al. (2008); Klotz et al. (2007, 2009)
		Linepithema humile	Fipronil + disodium octaborate tetrahydrate; bifenthrin granules; cyfluthrin spray	I	SS	Unclear	Klotz et al. (2007); Wiltz et al. (2009)
Perimeter spray and barriers treatments	Termites	*Reticulitermes flavipes*	Cypermethrin, fipronil	I	SS	Unclear	Ripa et al. (2007); Woodrow and Grace (2008)
		Coptotermes formosanus, Coptotermes. gestroi	Imidacloprid	I	DS	Unclear	Woodrow and Grace (2008); Osbrink et al. (2005); Zorzenon and Campos (2015)
		Coptotermes gestroi	Thiamethoxam	I	SS	Successful	Zorzenon and Campos (2015)
		Reticulitermes Hesperus, termite species	Non-toxic physical barriers	I	DS	Successful	Smith and Rust (1990); Lenz et al. (1997); Peters and Fitzgerald (1997); Woodrow and Grace (2008); Rust and Su (2012)
		Reticulitermes hesperus	Chlorfenapyr (BASF-Phantom(R))	I	SS	Successful	Rust and Saran (2006)
		Subterranean termite species	Chlorpyrifos, permethrin, cypermethrin, bifenthrin, fenvalerate (soil liquid insecticides)	I	SS	Unclear	Su and Scheffrahn (1998); Woodrow and Grace (2008); Lee et al. (2007)
		Subterranean termite species	Insecticide impregnated in polymer barriers	I	SS	Successful	Woodrow and Grace (2008); Su (2002)
		Specific species	Fumigation with carbon dioxide, methyl bromide, phosphine, sulfuryl fluoride	I	SS	Unclear	Myles (2005)
		Termite species	Wood treatment with *Ricinus communis* plant extracts	I	DS	Unclear	Sharma et al. (1991)
		Subterranean termite species	Imidacloprid + fipronil (fumigation)	C	SS	Unclear	Su (2002); Parman and Vargo (2010)

(*continued*)

Table 1. (*Continued*)

Control strategies	Group	Species	Strategy	Level treatment	Target species	Result	References
		Termite species	Soil treatments, wood treatments, foundation treatments and mechanical alterations	I	DS	Unclear	Milano and Fontes (2002)
Repellents	Ants	*Solenopsis invicta*	Essential balm	I	SS	Successful	Wen et al. (2016)
		Camponotus melanoticus, C. novograndensis Dorymyrmex thosoracicus	Essential oil *(Pogostemon cablin)*	I	SS	Successful	Albuquerque et al. (2013)
		Solenopsis invicta	Granular bifenthrin	I	SS	Successful	Pranschke et al. (2003)
Repellents	Termites	Termite species	Essential oils	I	DS	Successful	Verma et al. (2009); Manzoor et al. (2012); Cheng et al. (2014)
		Subterranean termite species	Dichloromethane and methanol extract of the Meliaceae family	I	DS	Unclear	Inacio and de Carvalho (2012)
		Coptotermes formosanus	Fungus (*Metarhizium anisopliae*)	I	SS	Successful	Sun et al. (2008)
		Coptotermes formosanus	Acoustic devices used in tandem with motion detection scanning microwave systems	I	SS	Successful	Austin et al. (2008)
Repellents	Wasps	Vespid species	Algaecide *n*-alkyl dimethyl benzyl ammonium chloride in swimming pool water	I	DS	Successful	Wagner (1980)
		Vespula pensylvanica, V. germanica, Polistes dominula	Essential oils	I	DS	Unclear	Zhang et al. (2013); Buteler et al. (2016)
Toxic baits	Ants	*Solenopsis invicta*	Hydramethylnon (AMDRO®), pyriproxyfen (Distance®-IGR)	C	SS	Unsuccessful	Greenberg et al. (2015)
		Linepithema humile	Disodium octaborate tetrahydrate	C	SS	Successful	Greenberg et al. (2006)
		Acromyrmex subterraneus subterraneus, Linepithema humile, Solenopsis invicta	Fipronil	C	SS	Successful	Collins and Callcott (1998); Rust et al. (2003); Vega and Rust (2003); Soeprono and Rust (2004); Choe and Rust (2008); Choe et al. (2010); Klotz et al. (2010); Gandra et al. (2016)
		Linepithema micans, Solenopsis invicta	Hydramethylnon, boric acid	C	SS	Successful	Drees et al. (1992); Nondillo et al. (2016)
		Linepithema humile	pheromone component ((Z)−9-hexadecenal) + insecticidal bait	C	SS	Successful	Sunamura et al. (2011); Welzel and Choe (2016)
		Linepithema humile	Boric acid	I	SS	Unsuccessful	Brightwell and Silverman (2009)
		Linepithema humile, Camponotus mus	Boron toxic bait (boric acid—borax)	I	SS	Unclear	Sola et al. (2013)
		Ant species	Pheromone-assisted techniques + insecticide baits	C	DS	Successful	Choe et al. (2015)
		Solenopsis invicta, S. geminata, S. richteri, M. destructor, W. auropunctata, Acromyrmex gracilipes, P. longicornis, T. melanocephalum	Different baits formulated	C	DS	Unclear	Stanley (2004)
		Linepithema humile	Different baits formulated	C	SS	Unclear	Knight and Rust (1991)
		Solenopsis invicta, Tapinoma melanocephalum	Methoprene baits	C	SS	Successful	Wiliams et al. (2001); Gusmao et al. (2011)
		Solenopsis invicta	Teflubenzuron	C	SS	Successful	Williams et al. (1997)
		Solenopsis invicta	Spinosad	C	SS	Unclear	Williams et al. (2001)
		Ant species	Trail pheromones, foliar spray, systemic insecticides	C	DS	Unclear	Rust and Su (2012)
		Lasius niger	Aspartame + jelly food	I	SS	Unsuccessful	Sorvari and Haatanen (2014)
		Linepithema humile	Imidacloprid	C	SS	Successful	Rust et al. (2003); Blight et al. (2011)
		Linepithema humile	Acetamiprid; bifenthrin; chlorfenapyr; cyfluthrin; indoxacarb; thiamethoxam	C	SS	Unsuccessful	Choe and Rust (2008)
		Linepithema humile	Disodium octaborate tetrahydrate	C	SS	Unclear	Klotz et al. (2007)
		Myrmicinae, Dolichoderinae	Soybean oil + indoxacarb	C	SS	Unclear	Klotz, Hansen, et al. (2008); Klotz et al. (2010)
		Anoplolepis gracilipes; Linepithema humile	Sucrose solutions + fipronil, indoxacarb, triamethoxam, boric acid	C	SS	Successful	Chong and Lee (2009); Klotz et al. (2009)

(*continued*)

Table 1. (*Continued*)

Control strategies	Group	Species	Strategy	Level treatment	Target species	Result	References
Toxic baits	Termites	Subterranean termite species	Imidacloprid bait	C	SS	Unclear	Osbrink et al. (2005); Xing et al. (2007)
		Termite species	Fipronil (TERMIDOR®)	C	DS	Successful	Verma et al. (2009); Scheffrahn et al. (2014)
		Subterranean termite species	Fipronil + straw pulp + white sugar	C	SS	Successful	Huang et al. (2005)
		Coptotermes gestroi	Fipronil	C	SS	Successful	Casarin et al. (2009)
		Coptotermes gestroi	Boric acid	I	SS	Successful	Casarin et al. (2009)
		Subterranean termite species	Hexaflumuron + monitoring plans	C	DS	Successful	Su and Scheffrahn (1998); Gambetta et al. (2000); Lee (2002); Yudin (2002)
		Subterranean termite species	Hexaflumuron bait	C	DS	Successful	Sajap et al. (1999); Grace and Su (2001); Vargo (2003)
		Heterotermes indicola, Reticulitermes jeauipes	Permethrin microencapsulated	C	SS	Successful	Schoknecht et al. (1994)
		Termite species	Plant extract	I	SS	Successful	Verma et al. (2009)
		Termite species	Bifenthrin, chlorfenapyr, cypermethrin, fipronil, imidacloprid, permethrin	C	SS	Unclear	Verma et al. (2009)
		Coptotermes formosanus	Bistrifluron bait	C	SS	Unclear	Kubota et al. (2006)
		Incisitermes snyderi, Cryptotermes brevis	Disodium octaborate tetrahydrate, calcium arsenate, and chlorpyrifos	C	SS	Unclear	Scheffrahn et al. (1997)
		Termite species	Essential oils	I	DS	Unclear	Verma et al. (2009)
		Coptotermes formosanus, Reticulitermes flavipes	Hexaflumuron and diflubenzuron	C	SS	Unclear	Su and Scheffrahn (1993)
		Subterranean termite species	Hexaflumuron, diflubenzuron, sulphluramid	C	SS	Unclear	Su (2002)
		Reticulitermes flavipes	Hexaflumuron, sulphluramid bait	C	SS	Unclear	Ripa et al. (2007)
		Subterranean termite species	Noviflumuron, fipronil and thiamethoxam bait	C	SS	Unclear	Su (2005)
		Reticulitermes flavipes	Resin-based transmissible coating (sulphluramid)	C	SS	Successful	Myles (1996)
Toxic baits	Wasps	*Vespula germanica*	Hydramethylnon, permethrin and chlorpyrifos + protein bait	C	SS	Unsuccessful	Sackmann and Corley (2007)
		Vespula vulgaris	Fipronil (XtinguishTM)	C	SS	Successful	Harper et al. (2016)
		Vespula pensylvanica, V. germanica, Polistes dominula	Fipronil + chicken + heptyl butyrate	C	SS	Successful	Hanna et al. (2012)
		Vespula germanica, V. vulgaris, V. pensylvanica	Fipronil + minced beef	C	SS	Successful	Spurr (1991); Gambino and Loope (1992); Beggs et al. (1998); Harris and Etheridge (2001); Sackmann et al. (2001); Wood et al. (2006)
		Vespula germanica	Fipronil + minced white chicken	C	SS	Successful	Sackmann and Corley (2007)
		Vespula spp.	Fipronil + sugar syrup	C	DS	Successful	Harris and Etheridge (2001)
		Vespula vulgaris, V. germanica	Fipronl + green-lipped mussel volatiles	C	SS	Successful	Unelius et al. (2014)
		Vespula spp.	Chlorfenapyr, chlorantraniliprole, indoxacarb, spinosad + chicken or fish	C	DS	Unclear	Rust et al. (2009)
		Vespa velutina	Fipronil + sweet beer	C	SS	Unclear	Dauphin and Thomas (2009); Rome et al. (2011)
		Vespula spp.	Pyrethroid insecticide (ONSLAUGHT ™)	C	DS	Unclear	Rust et al. (2009)

Note: C, colony; I, individual. By colony-level treatment we included all treatments that are applied directly to the nest or could be transmitted among workers or from workers to reproductives, but ultimately killing the colony (for example: toxic baits). The individual-level treatment encompasses treatments that affect only individual workers, without having as a purpose any direct effects on the colony as a whole (for example: repellents or traps).

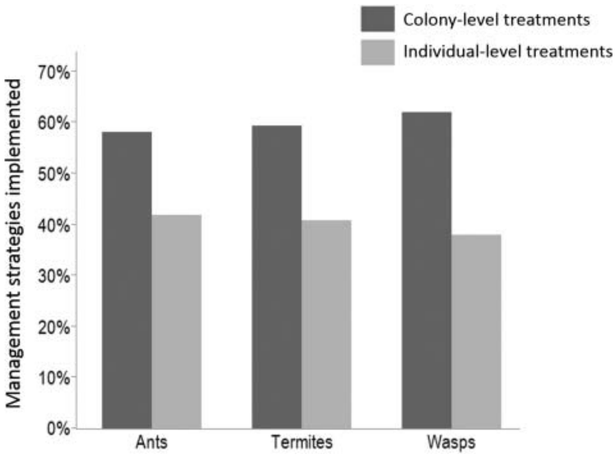

Figure 1. Proportion of management strategies implemented on colony-level treatment and individual-level treatment of ants, termites and wasps.

workers may cause to human activities, rather than the reduction of the population (for example: repellents or traps).

The studies that evaluated management strategies for invasive social insect species are generally species-specific (68.8%) and in most cases are reported to have achieved an effective control. By contrast, when the strategy was not species-specific and was applied to a group of different species, results are more variable, having successful and unsuccessful results depending on the context in which it is applied. Although within their native distribution, ants and termites have often become important pests in urban environments, and different management strategies have been implemented for each particular group, most control efforts have focused on non-native species regardless of taxonomic affiliation (native: 15.6% vs. non-native: 84.4%).

In terms of the control methods used to manage social insects, there are two main approaches: chemical and non-chemical control (Figure 2 and Table 1). We found that most studies on chemical control rely largely on the use of toxic baits. This method is based on the trophallactic behaviours displayed by ants and wasp (but not termites), and is the most effective practice implemented. Nest treatment is another applicable approach to control social insects, but as often occurs with some ant and wasp species, the identification of nest location can be difficult. Within the non-chemical strategies, biological control is the main approach. However, results suggest that this practice is largely inefficient, probably due to the guarding and hygienic behaviours displayed by many social species, where nestmates avoid non-kin from entering the colony or else remove alien or suspicious elements from the nest (Grace 1997; Beggs et al. 2002; Wilson-Rich et al. 2009).

Another strategy that is implemented with or without associated toxic baiting is the perimeter or barrier treatment. This tactic is mainly used for termite and ant control as these insects forage by walking, however the types of baits effected to kill termites and ants are different (i.e. termites do not do oral trophallaxis). There are several known strategies that are implemented in new building foundations (such as insecticide-impregnated polymer barriers, or sand or gravel aggregates) with effective results. However, their effect on the reduction of populations of termites is limited, being their main objective to avoid the contact of termites with humans or the damage produced by individual foragers.

With the aim of eliminating insects from human dwellings, and given the difficulties set by their structure, pesticides are commonly used (Table 1). Lack of alternative methods has led to the overuse of insecticides to control some of these urban pests, leading to unwanted health issues (Landrigan et al. 1999). Despite this, some studies suggest that people tend to reject the

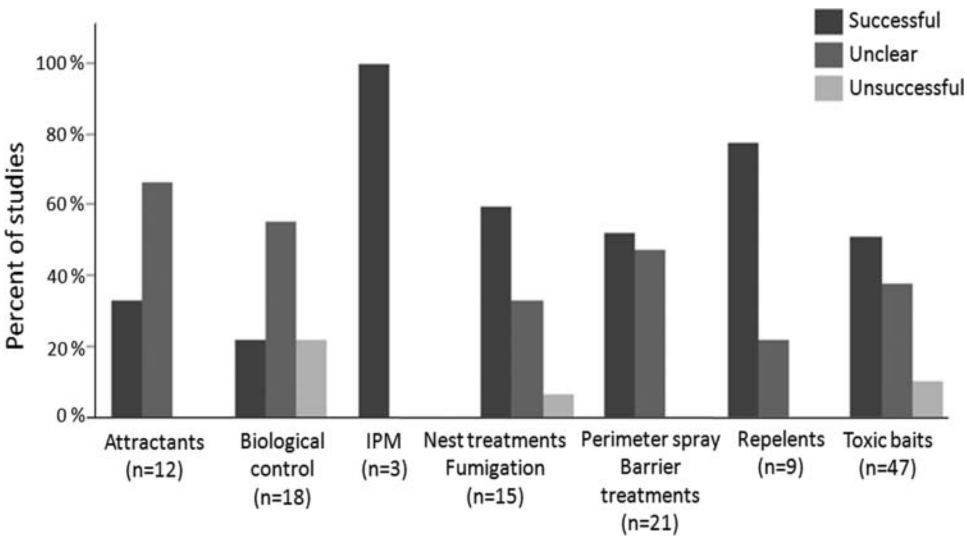

Figure 2. Percentage of studies with successful, unclear or unsuccessful results found with different control strategies against social insect pests in urban environment. Note that some studies mention more than one strategy.

use of strategies that are environmentally safe, yet less effective than chemical control (e.g. Robinson 1996). IPM, for example, has been rarely approached to manage control of social insect pests in metropolitan environments. IPM is a broad-based approach where not a single control method is used but rather involves integrating multiple control methods, with the rational use of pesticides (Prokopy 2003). The key idea in urban IPM consists in eliminating or reducing food and shelter available to pests (Sarisky et al. 2008). We found only three studies that used IPM and that reported successful results (Figure 2). One case accounts for its application to termites in China in 2001, and consisted in the use of a baiting system with low toxicity, thus eliminating two persistent organic pollutants commonly used to control these insects (Anonymous 2007; Table 1). The other cases included an area-wide management effort to eradicate *Linepithema humile* in New Zealand, and *Lasius neglectus* in north-east Spain and continental Europe. Both are reported as successful albeit in reducing, but not eliminating, Argentine ant populations there (Rey & Espadaler 2004; Ward et al. 2010; Table 1).

Managing social insect populations via worker population reduction: is this possible?

Management of social insect species, including those found in urban habitats, is generally undergone through two different tactics: the control at the colony-level or at the individual-level (Table 1). Fewer efforts have been devoted to the control of the individual workers with the aim of reducing the population size. For example, for non-native wasps in New Zealand, Beggs et al. (2011) have suggested that given the redundancy of adults, capturing them with attractive traps, has a minimal effect on the wasp population. Another study found that the experimental removal of up to 75% of *Polistes* spp. adults from nests reduced colony size by only 29%–34% five weeks later (Toft & Harris 2004). This strategy has not been extensively studied in highly social species, partly because massive capture of workers is needed and even then, this rarely translates into population suppression (Courchamp et al. 2008).

For the removal of individual workers to impact population growth of social insects, Allee dynamics could potentially be exploited in the design and implementation of eradication and containment programs (Allee et al. 1949; Courchamp et al. 2008). Allee effects are defined as the positive relationship between any component of the total individual fitness of a species and either numbers or density of conspecifics (Stephens et al. 1999; Kramer & Drake 2010). Such Allee effects, termed demographic Allee effects, may be generated by various mechanisms (known as component Allee effects) that could work separately or multiple acting simultaneously (Berec et al. 2007). Well-known examples of component Allee effects are problems in mate-finding or reduced foraging efficiency in small populations. Regarding survival problems generated when populations are not large enough, these may arise through a deficient cooperative foraging, breeding or anti-predatory behaviours (Berec et al 2007; Courchamp et al. 2008). The Allee effect concept is now recognized as a ubiquitous phenomenon in natural populations with important implications in many fields of evolution, ecology and population management (Stoner & Ray-Culp 2000; Wertheim et al. 2002; Kuussaari et al. 1998; Luque et al. 2013).

Eusocial species, by definition, are obligate cooperative animals and have a need for conspecifics, whether for cooperative hunting and foraging, rearing of offspring, protection from predators, reproductive opportunities or some other mechanisms, or (usually) a combination of many factors (Wilson 1975; Courchamp et al. 1999; Clutton-Brock 2002; Courchamp et al. 2008). This implies that for social insect species there is a critical number of workers necessary for colony success (i.e. the Allee threshold). Critical population (colony) sizes, below which the per capita growth rate becomes negative, are called, the Allee threshold. One way of recognizing the existence of an Allee threshold could be evaluating the quality of queens in relationship with the colony size, or through the impact of pathogens on nest hygiene.

Various programs designed to interfere with mating are examples of the application of Allee thresholds in pest management in agricultural and urban environments. A well-known case is that of the sterile insect technique, where large numbers of sterile males are reared and released in pest ridden areas (Knipling 1955; Hendrichs 2000). In selected urban locations in the United States, Australia and Japan the control of fruit flies is done by releasing sterile males to create a human-induced Allee effect (Krafsur 1998; Hendrichs et al. 2002). Despite the fact that in eusocial insects such as bees, wasps and ants, large colonies of numerous, strongly cooperating individuals is an evident characteristic and is consequently likely to be strongly exposed to the Allee effects, there are still a limited number of studies focusing on these in social insect pests, and how these might be manipulated to manage their populations (Beggs et al. 2011). In some cases, strong, intensive control of workers has been attempted (Williams et al. 2001), suggesting this may have an effect on the populations. Killing non-reproductive castes of social insect pests has been often successfully implemented in pest control practices (Choe & Rust 2008; Casarin et al. 2009; Choe et al. 2010), yet most efforts have focused on minimizing their presence, rather than on inducing Allee effects. This likely because ultimately it is the workers (and their large numbers) what mostly affects humans, as reproductives are much less and often remain most of their lives inside their nests. Moreover, in some cases such as that of the invasive Argentine ant (*L. humile*) populations in the USA, colonies are so big (known as supercolonies that can bear billions of individuals) that inducing Allee effects through worker control may be a daunting if not an impossible task (see Silverman & Brightwell 2008). There should be more species-specific studies to find the Allee thresholds below which given social insect populations could be locally controlled or even exterminated through worker control in low-density populations. Also, studies that investigate which are the component Allee effects that contribute to the demography of each species, may also help centre best our control or management efforts.

Concluding remarks

Managing social insect populations in urban environments is a standing challenge. Colonies are typically very numerous and many species have evolved social behaviours that allow them to successfully exploit the human habitat and in turn, limit the success of several practices commonly applied for the management of other insect pests. For example, social insects are known to guard their nests from alien organisms, affecting the application of several bio-control agents. Many species, such as the vespid wasps, are opportunistic scavengers that make use of human refuse and can build nests in man-made buildings (Spradbery 1973). In turn, various non-native ants expand their range by exploiting disturbed soil, such as that caused by road construction (Forys et al. 2002). The great plasticity that these species show could be an explanation for the large amount of studies carried out to manage or control them and the little satisfactory results found so far.

The results of this overview show that while some effort has been allocated to the development of control measures for insects in human dwellings and urban environments, successful results are still limited or species-specific. The use of toxic baits seems to be the most effective practice applied so far to reduce populations of most social insects, but reasonably, there is a growing concern on the use of pesticides in close proximity to people. Progress in the development of alternative methods remains slow, but will likely continue to be species-specific requiring a deeper understanding of the ecology of the organism to be managed and the factual implications of their presence and abundance in the human surroundings.

The fact that more than five times more pests are non-native than native gives support to the efforts of controlling for the accidental introduction of foreign urban pest species. Our findings which describe the reported control measures applied for social insect pest management, illustrate the importance of alien species in the urban setting. Given the immense daily movement of goods and people in and out of cities and how these become hubs of international trade (i.e. most major airports, ports and railway stations are in or close by to densely populated cities), suggests that a clear avenue for research involves developing simple methods for early detection of social insect pests before these establish in new metropolitan landscapes (Hulme 2009).

A challenge for the development of urban IPM programs in the household environment remains, not only to reduce pesticide usage, but to achieve effective and economical area-wide pest-free living spaces. The persistence of many social insect species in urban areas is based on a network of reservoir populations, from which individuals or groups move to infest or re-infest domestic or peri-domestic habitats. For IPM programs to be successful, reservoir populations and habitats must be identified and reduced (Robinson 1996). IPM practices that include the reduction of resources made available to insects are critical to sustainable success.

Another key area deserving careful research attention implies focusing on colony weaknesses. The mass trapping of workers can provide an interesting practice that can combine public perception of the pest problem with an effective reduction of noxious populations. This is because it often is worker activity through where social insects interact with humans. Species-specific studies on colony Allee thresholds, especially in non-native species, are likely to provide an interesting pathway for the control of social insects. Recall that eusociality implies cooperation which is underlined by potential Allee effects. Also, managing Allee thresholds has been shown to be effective in the control of other pests (Liebhold & Tobin 2008). For social insects, the emphasis would be set, rather than on finding and killing nests and reproductive females, on mass capturing workers. While this approach may imply large, area-wide and long-standing efforts, it could significantly reduce the use of pesticides in human habitations.

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