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The Emergence and Sustainability of Urban Entomology

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Abstract

Urban entomology is the study of arthropod and other pests of the urban environment. It has gained worldwide recognition as a distinct discipline. Its origin is associated with Walter Ebeling's publication *Urban Entomology* in 1975. Urbanization, invasive pests, increased demand for pest management services, and changes in legislation collided in the 1970s to create a need for research and extension activities worldwide. This resulted in urban entomology as a discipline and, within two decades, its national and international recognition. In this review, we present the factors that led to the development of urban entomology and how they have shaped its current meaning. As urbanization intensifies and the global economy increases, the demands for urban pest management will continue to grow. We discuss how these future challenges may shape and alter the discipline.

1. INTRODUCTION

Urban entomology is a discipline within entomology recognized worldwide as the study of household and structural pests. It has been embraced by researchers; academia; cooperative extension specialists; and pest management professionals (PMPs), who differ from traditional economic and medical entomology professionals. The earliest publications in the discipline include discussion of spiders; mites; ticks; and vertebrate pests such as rodents, bats, and birds (37–39).

The importance and relevance of this discipline extends from the emotional to the medical and includes the pest status of arthropods in the urban living space. The costs associated with the control of ants, cockroaches, bed bugs, termites, and other structural pests and their damage are substantial. In 2010, it was estimated that termites caused >US$40 billion in damage worldwide (86). The predicted annual growth rates of bed bug services of 4.7% in United Kingdom and 5.2% in Germany from 2016–2026 will cost approximately US$12 million and US$16 million per year, respectively. If similar growth rates occur across Europe, then total costs could be US$140 million (70). In 2019, the global market for pest control services was US$19.7 billion, and it is expected to increase to US$31.9 billion by 2027 (25). North America has 50% of the market share of the global pest management market, with a compound annual growth rate (CAGR) of 5%, but the highest market growth rate is in Asia (present market share of approximately US$4 billion), which has a CAGR of 8.5% (56). These figures do not include the direct sales of pesticides to homeowners.

Economics might be a factor in the emergence and relevance of urban entomology (22). The pest management industry's continuous growth has dictated the direction of urban entomology's research and extension efforts. The demand for pest management services requires improved equipment and technology, increased training of technicians, and regulatory changes.

The term urban entomology first appeared in an entomological note by A.H. Waters in 1884 about lepidopterans in the Cambridge area (104). The term was not defined, but readers were left with the impression that he was referring to insects associated with cities. Its use did not emerge again until the seminal book by W. Ebeling, *Urban Entomology*, in 1975 (21). In the preface, Ebeling cited a report from a joint task force of the United States Department of Agriculture (USDA) and land grant institutions that proposed five distinct categories of research: "1) Problems associated with farm and other outdoor labor, 2) Problems resulting from modification of the environment by man, 3) Insect pests of man in and around his buildings, 4) Problems associated with urbanization, and 5) Insect pest problems in recreational areas" (21, p. iv). Categories 3, 4, and 5 have become the focus of urban entomology and pest management. The study of arthropod pests of plants in urban landscapes and that of pests of medical and veterinary importance are separate disciplines. The term urban entomology commonly appears in publication titles after 1975 (**Table 1**).

Urban entomology has been widely recognized without any definitive definition being accepted (90). Robinson (81, p. xiii) defined urban entomology as ". . .the discipline of science that includes the life history and control of arthropods that interact with people, pets and plants in the human environment—whether in an urban or a rural setting." Zungoli (111, p. 61) defined it as "the study of arthropods in association with humans and their structures." Ebeling (21) excluded pests of plants, based on the practical consideration that someone more qualified should discuss these, but included vertebrate pests. In this review, the following definition has been adopted: Urban entomology is the study of arthropods and pests of the human environment.

Disciplines with an emphasis on fundamental research, such as genetics, physiology, biochemistry, and toxicology, are generally driven by extramural funding from government agencies (federal and state in the United States). Urban entomology had a different, perhaps unique, origin. Urban entomology developed as a response to urbanization, increased demands for pest management services, invasive pests, increased awareness of pesticides, and a need to extend information

Table 1 Titles, years of publication, and geographic focuses of books related to urban entomology and urban pests

Year	Title	Geographic focus	Author(s) (Reference)
1934	*Termites and Termite Control*	North America	Kofoid et al. (51)
1935	*Our Enemy the Termite*	North America	Snyder (89)
1939	*202 Common Household Pests of North America*	North America	Hartnack (37)
1941	*Insect Pests*	United Kingdom	Harvey & Hill (39)
1943	*Unbidden House Guests*	North America	Hartnack (38)
1945	*Handbook of Pest Control; the Behavior, Life History, and Control of Household Pests*	North America	Mallis (62)
1952	*Australian Termites: The Biology, Recognition, and Economic Importance of the Common Species*	Australia	Ratcliffe et al. (75)
1962	*Scientific Guide to Pest Control Operations*	North America	Truman & Butts (95)
1962	*Pests of Australian Homes and Industry*	Australia	Hadlington (32)
1963	*The Insect Factor in Wood Decay: An Account of Wood-Boring Insects with Particular Reference to Timbers Indoors*	United Kingdom, Europe	Hickin (41)
1963	*The Woodworm Problem*	United Kingdom, Europe	Hickin (42)
1963	*The Dry Rot Problem*	United Kingdom, Europe	Hickin (40)
1964	*Household Insect Pests*	United Kingdom, Europe	Hickin (43)
1965	*Recognition of Structural Pests and Their Damage*	North America	Sweetman (91)
1965	*The Termites of the United States—A Handbook*	North America	Weesner (105)
1967	*The Conservation of Building Timbers*	United Kingdom, Europe	Hickin (44)
1968	*The Cockroach: A Laboratory Insect and an Industrial Pest*	Worldwide	Cornwell (12)
1969	*Biology of Termites*, Vol. I	Worldwide	Krishna & Weesner (52)
1970	*Biology of Termites*, Vol. II	Worldwide	Krishna & Weesner (53)
1971	*Termites: A World Problem*	Worldwide	Hickin (45)
1973	*Pest Control in Buildings: A Guide to the Meaning of Terms*	Worldwide	Cornwell (13)
1975	*Urban Entomology*	North America	Ebeling (21)
1976	*The Cockroach: Insecticides and Cockroach Control*	Worldwide	Cornwell (14)
1978	*Perspectives in Urban Entomology*	North America	Frankie & Koehler (26)
1980	*Urban Pest Management*	North America	Committee on Urban Pest Management (11)
1980	*Social Wasps—Their Biology and Control*	United Kingdom, Europe	Edwards (22)
1983	*The Ratcatcher's Child: The History of the Pest Control Industry*	North America	Snetsinger (88)
1985	*Bookworms: The Insect Pests of Books*	United Kingdom, Europe	Hickin (46)
1985	*Pest Animals in Buildings: A World Review*	United Kingdom, Europe	Hickin (47)
1985	*Urban Pest Control in Australia*	Australia	Hadlington & Gerozisis (34)
1986	*Advances in Urban Pest Management*	North America	Bennett & Owens (8)
1986	*Economic Impact and Control of Social Insects*	North America, United Kingdom	Vinson (101)
1986	*Termites in Buildings: Their Biology and Control*	Worldwide	Edwards & Mill (23)
1987	*Australian Termites and Other Common Timber Pests*	Australia	Hadlington (33)
1987	*Biology and Control of the Formosan Subterranean Termite: Proceedings of the International Symposium on the Formosan Subterranean Termite*	North America, Asia	Tamashiro & Su (92)

(*Continued*)

Table 1 (*Continued*)

Year	Title	Geographic focus	Author(s) (Reference)
1992	*NPMA Field Guide to Structural Pests*	North America	Smith & Whitman (87)
1995	*Understanding and Controlling the German Cockroach*	Worldwide	Rust et al. (85)
1996	*Urban Entomology—Insect and Mite Pests in the Human Environment*	Worldwide	Robinson (81)
1997	*Termites—Biology and Pest Management*	Worldwide	Pearce (69)
1998	*Biology and Control of Termites in China*	China	Liu et al. (61)
1998	*Termites and Borers: A Homeowner's Guide to Detection and Control*	Australia	Hadlington & Stanton (35)
1999	*Urban Pest Control—A Malaysian Perspective*	Southeast Asia	Lee et al. (60)
2000	*Handbook of Household and Structural Insect Pests*	North America	Gold & Jones (28)
2001	*Pest Management in Museums, Archives and Historical Houses*	North America	Pinniger (73)
2004	*Guide to Urban Pest Ants of Singapore*	Southeast Asia	Lee & Tan (59)
2005	*Carpenter Ants of the United States and Canada*	North America	Hansen & Klotz (36)
2005	*Urban Insects and Arachnids: A Handbook of Urban Entomology*	Worldwide	Robinson (82)
2007	*Bed Bug Handbook: The Complete Guide to Bed Bugs and Their Control*	North America	Pinto et al. (74)
2007	*Perspective in Urban Insect Pest Management in Malaysia*	Southeast Asia	Lee (54)
2008	*Urban Ants of North America and Europe—Identification, Biology and Management*	North America, Europe	Klotz et al. (49)
2008	*Public Health Significance of Urban Pests*	Worldwide	Bonnefoy et al. (9)
2009	*Pest Cockroaches of Singapore—A Scientific Guide for Pest Management Professionals*	Southeast Asia	Lee & Ng (58)
2009	*Urban Entomology*	China	Zhang (110)
2009	*Pesticides in Household, Structural and Residential Pest Management*	North America	Peterson & Stout (72)
2011	*Urban Pest Management: An Environmental Perspective*	Worldwide	Dhang (16)
2012	*Termite Research in Japan—From Biodiversity to Control*	Japan	Yoshimura et al. (109)
2014	*Urban Insect Pests: Sustainable Management Strategies*	Worldwide	Dhang (17)
2014	*Termites of Singapore—A Scientific Guide for Pest Management Professionals*	Southeast Asia	Lee (55)
2016	*Studies on Urban Cockroaches in Japan*	Japan	Tsuji (98)
2017	*Climate Change Impacts on Urban Pests*	Worldwide	Dhang (18)
2018	*Advances in the Biology and Management of Modern Bed Bugs*	Worldwide	Doggett et al. (20)
2019	*Timber Decay in Buildings and Its Treatment*	United Kingdom, Europe	Ridout (76)
2021	*Biology and Management of the German Cockroach*	Worldwide	Wang et al. (102)

to PMPs and the public. Entomology departments in land grant universities in the United States and research organizations worldwide provided the scientific foundation and facilities for research. The professional pest control industry has provided vocal and economic support for the emerging discipline.

This review provides an in-depth accounting and history of the emergence of urban entomology and examines factors that impacted the development of the discipline and how it is likely to evolve.

2. URBAN ENTOMOLOGY IN THE LITERATURE

Numerous publications have contributed to our understanding of urban entomology and its development as a discipline (**Table 1**). Early contributions dealt with pests in the United States, United Kingdom, and Europe, but in recent years, greater attention has been given to urban pests from Northeast and Southeast Asia.

The first comprehensive books on household pests were *202 Common Household Pests of North America* in 1939 (37) and *Unbidden House Guests* in 1943 (38), both by H. Hartnack, and *Insect Pests* in 1941 (39), by W.M. Harvey and H. Hill. Among the pests covered were rats and mice, birds, silverfish, crickets, cockroaches, termites, booklice, stored product insects, mosquitoes, and bed bugs, and the emphasis was on the damage that they cause and on control measures. Hartnack (37) insisted that thoroughness of inspections and pest prevention were signs of professional competence and business integrity; his views were often controversial and ahead of his time (88). In the United Kingdom, Harvey & Hill (39, p. v) wrote, "What was formerly and far too often considered little more than a nuisance, has now been finally recognized as a definite menace."

The *Handbook of Pest Control* (62) by A. Mallis in 1945 provided information on the biology and control of structural pests, including vertebrates. It was a reference book for PMPs and academics. Another important training manual was the *Scientific Guide to Pest Control Operations* (95), first published in 1962. Both publications have had numerous revisions, and they may be the most widely circulated texts worldwide on urban entomology.

One of the most productive and influential authors dealing with urban pests was N. Hickin. He was the Technical Manager and Scientific Director from 1944 to 1972 at Rentokil Limited pest control company, based in the United Kingdom. He was a world authority on the wood-boring beetle family Anobiidae (6). He wrote a series of books on pests of urban structures in the United Kingdom and Europe; these are collectively referred to as the Rentokil Library (**Table 1**).

In the mid-1950s, W. Ebeling at the University of California, Los Angeles and associates began a research program on arthropods and insects in urban settings in the western United States. They published numerous papers on ants, cockroaches, termites, yellowjackets, and fabric pests. Their work culminated in *Urban Entomology* in 1975 (21), with a second printing in 1978. The chapters were organized around the foods and habitats of the pests instead of pest groups. A brief discussion of insects of house plants was included, but pests of plant landscapes were not mentioned. Vertebrate pests such as rodents, bats, birds, and venomous snakes were discussed because PMPs encounter them when servicing clients.

In Australia, P. Hadlington was an early contributor, publishing several books dealing with pests in the urban environment, and is probably best known for *Urban Pest Control in Australia* (34), written with J. Gerozisis (**Table 1**). As early as 1956, he provided training for the PMPs and was a strong advocate of professionalism in the industry (93). Among the earliest published research on urban insect pests in Asia were investigations on the feeding behavior and preferences of cockroaches in Japan in the 1960s (96, 97). In China and Southeast Asia, cockroach research started with surveys of species infesting urban dwellings (67, 83, 107, 108). The earliest applied termite research in Southeast Asia was on species attacking trees in forests and plantations (94). Research on termites affecting buildings and structures in the urban environment in Southeast Asia begin in the 1990s, when chlordane was banned.

The focus of urban pest management on pests associated with human buildings, food supplies, and health and welfare broadened the scope of economic entomology beyond traditional agriculture. In 1992, the *Journal of Economic Entomology* included the section Household and Structural Insects. The *Journal of Agricultural Entomology* was renamed the *Journal of Agricultural and Urban Entomology* in 1999.

3. FACTORS CONTRIBUTING TO THE IMPORTANCE OF URBAN ENTOMOLOGY

Before 1975, researchers were already conducting research on various urban pests worldwide. An estimated 17.2 scientist years at various agricultural experiment stations in the United States were devoted to multiple urban insect pests (79). In 1996, Zungoli (111) compiled a list of resources and laboratories outside the United States devoted to urban entomology. The facilities were understaffed or nonexistent in Central and South America. However, the number of researchers and extension specialists in urban entomology has dramatically increased worldwide since 1975 (**Table 2**).

3.1. Urbanization

The world population is dramatically shifting from rural to urban areas. Global urbanization has increased the importance of urban entomology research and extension. The magnitude of these changes is influenced by how urban populations are defined, but the trend is undeniable. The current estimate of the urban population is approximately 4.5 billion (78). In some parts of Western Europe, the Americas, Japan, and Australia, 80% of the population lives in urban areas. By 2050, it is estimated that 68% of the world's population will live in urban areas (99).

The impact of this shift on urban pest management has been significant and created demands on agencies and institutions worldwide. The increase in urban population has resulted in inadequate housing and infrastructure and created conditions favorable to vectors and reservoirs of communicable disease (50). As urban habitats expanded, natural habitats were eliminated, and urban and fringe habitats took their place. Some arthropods and insects became facultative synanthropes. Over centuries, some of the most important urban pests have become obligatory synanthropes (63, 81).

The complexity of the urban environment contributes to pest problems (81). A range of habitats, such as parks and green space, sanitary and sewer systems, solid waste disposals and landfills, and urban agriculture, provide harborage and food for pests. For example, as the degree of urbanization increased, the intensity of disgust toward insects indoors on the part of Japanese homeowners also increased (27). Urbanization will likely increase the need for pest management actions, as accidental invaders will be considered pests.

3.2. Invasive Pests

Urbanization and expanding global markets have increased the movement of household and structural pests. Species of ants, cockroaches, stored product pests, and flies are distributed worldwide, and some are considered invasive in the new locations (84). As the level of international trade increases, the number of invasive alien pest species also increases (106). Some are highly adapted to modified human environments (63), while others compete with existing species to become established. For example, in 1969, 17 species of termites were considered invasive; by 2013, there were 28 such species worldwide (24). The economic and health threat of invasive species drives the need for basic research, new pest management strategies, and the exchange of information.

3.3. Pest Resurgence

Urban insect pest species can have a resurgence in pest status or increase their distribution because of high levels of resistance to previously effective insecticides. This scenario can result in reduced efficacy of pest management strategies. The worldwide resurgence of bed bugs, *Cimex lectularius* L. and *Cimex hemipterus* (F.), is an example. *Cimex hemipterus* is primarily distributed

Table 2 Researchers in urban entomology from 1940 to the present

Researcher	Affiliation	Years active[a]	Research areas and notable contributions
Menandro Acda	University of the Philippines	2004–	Biology and control of termites in the Philippines
Roger Akre	Washington State University	1964–1994	Biology and control of yellowjackets and carpenter ants
Arthur Appel	Auburn University	1983–	Biology and control of cockroaches, environmental physiology of urban pests
Daniel Bajomi	Balbona Bio, Hungary	1971–	Rodent and ant control in Hungary
Paul Baker	University of Arizona	2000–2020	Biology and control of the subterranean termite, *Heterotermes aureus*
Gary Bennett	Purdue University	1967–2020	Behavior and control of cockroaches and pest ants
Eric Benson	Clemson University	1997–2019	Biology and control of cockroaches, termites, bed bugs, and pest ants
Clive Boase	Pest Management Consultancy, United Kingdom	1982–	Biology and control of urban and industrial pests, ICUP
Warren Booth	University of Tulsa, Virginia Tech	2007–	Evolutionary biology and molecular ecology of urban insect pests
Richard Brenner	USDA-ARS	1987–2001	Biology and control of cockroaches, cockroach allergens
Nancy Breisch	University of Maryland	1994–2021	Biology of termites, IPM in buildings
Grzegorz Buczkowski	Purdue University	2001–	Biology and control of invasive urban pest ants
Ana Eugênia De Carvalho Campos	Instituto Biológico, Brazil	1999–	Ecology and diversity of urban pest ants in Brazil
Dong-Hwan Choe	University of California, Riverside	2006–	IPM strategies, biodegradable hydrogel baits
Thomas Chouvenc	University of Florida	2008–	Biology and control of Formosan and Asian subterranean termites
Donald Cochran	Virginia Tech	1957–1999	Cockroach physiology, insecticide resistance in the German cockroach
Mary Cornelius	USDA ARS	1994–	Biology and control of the Formosan subterranean termite
Ana Maria Costa-Leonardo	São Paulo State University, Brazil	1987–	Biology of the Asian subterranean termite in Brazil
Michael Crosland	Chinese University of Hong Kong, University of Florida	1990–2006	Termite biology
Zachary DeVries	NCSU, University of Kentucky	2013–	Biology and novel control strategies against cockroaches and bed bugs, spatial dynamics of histamine in bed bug–infested homes
Stephen Doggett	Westmead Hospital, Australia	1989–	Bed bug biology and control, best practices for bed bug control
Virginia Durier	Université de Rennes I, France	1998–2016	Cockroach behavior
Walter Ebeling	University of California, Los Angeles	1946–1984	Repellency in cockroaches, alternative pest control, authored *Urban Entomology* and coined the name of the discipline
John Edwards	Central Science Laboratory, Slough, United Kingdom	1975–1995	Biology and control of the Pharaoh ant

(*Continued*)

Table 2 (*Continued*)

Researcher	Affiliation	Years active[a]	Research areas and notable contributions
Olga Eremina	Scientific Research Disinfectology Institute, Russia	1996–	Control of urban insect pests in Russia, insecticide resistance
Theodore Evans	CSIRO Australia, National University of Singapore, University of Western Australia	1995–	Evolution, ecology of sociality, and control of termites
Gordon Frankie	University of California, Berkeley	1971–2020	Urban pest ecology, urban bees
Brian Forschler	University of Georgia	1994–	Termite population genetics, IPM, termite biology
Roger Gold	University of Nebraska, Texas A&M University	1981–2015	Biology and control of cockroaches, termites, and ants; pesticide residue analysis
J. Kenneth Grace	University of Hawaii	1985–2020	Termite biology and control
Albert Greene	US General Services Administration	1975–2021	Biology of vespine wasps, IPM in buildings
Ameya Gondhalekar	Purdue University	2011–	Biology and control of cockroaches and bed bugs, insecticide resistance
James Grayson	Virginia Tech	1947–1979	Biology of the German cockroach, insecticide resistance
Les Greenberg	Texas A&M University; University of California, Riverside	1985–2021	Biology and control of the red imported fire ant and Argentine ant, insecticide runoff in urban settings
Ayodhya Gupta	Rutgers University	1973–1997	Juvenile hormone effects on cockroaches
Phil Hadlington	New South Wales Forestry Commission	1947–1995	Termites and wood-destroying pests, training pest control technicians
Philip Hamman	Texas A&M University	1965–1986	Extension and research on urban insect pests
Laurel Hansen	Spokane Falls Community College	1985–	Biology of carpenter ants
Michael Haverty	USDA Forest Service	1970–2022	Biology and control of termites, cuticular hydrocarbon analysis
Gregg Henderson	Louisiana State University	1990–2021	Biology and control of the Formosan subterranean termites
Claudia Husseneder	Louisiana State University	1998–	Population genetics and breeding systems of termites
Susan Jones	US Forest Service, Ohio State University	1987–2021	Biology and control of termites and bed bugs
Shripat Kamble	University of Nebraska	1985–2018	Biology and control of cockroaches, termites, and bed bugs
Bradford Kard	Oklahoma State University	1990–	Termite biology and control, termiticide testing
Ayako Katsumata-Wada	Kyoto Institute of Technology, Kyoto University, NCSU	2000–	Glucose aversion in the German cockroach, chemical ecology
Stephen Kells	University of Minnesota	1998–	IPM in urban and industrial settings for the control of bed bugs, cockroaches, and stored product insects
John Klotz	University of California, Riverside	1990–2009	Ant structural guidelines, foraging behavior, and baiting

(*Continued*)

Table 2 (*Continued*)

Researcher	Affiliation	Years active[a]	Research areas and notable contributions
Heinrich Kemper	Prussian State Institute for Water, Soil and Air Hygiene; Free University	1925–1969	Biology and control of bed bugs, insect pests of food and textiles, training pest control technicians
Phillip Koehler	University of Florida	1975–	Biology and control of cockroaches, fleas, and other urban pests
Jeffery LaFage	Louisiana State University	1974–1989	Biology and control of Formosan subterranean termites
Isabelle Landau	Urban Pest Advisory Service, Zurich (Switzerland)	1997–	Urban pest monitoring and control in Switzerland
Chow-Yang Lee	Universiti Sains Malaysia; University of California, Riverside	1993–	Insecticide resistance, biology, and control of urban insect pests in Southeast Asia and the United States
Michael Lenz	CSIRO Australia	1975–2011	Biology and control of termites in Australia
Vernard Lewis	University of California, Berkeley	1991–	Drywood termite detection and control
Houfeng Li	National Chung Hsing University, Taiwan	2008–	Termite biology and ecology in Taiwan
Clifford Lofgren	USDA ARS	1961–2001	Control of red imported fire ants
Arnold Mallis	University of California, Los Angeles; Gulf Oil; Pennsylvania State University	1939–1975	Ant control in California, authored *Handbook of Pest Control*
Abdul Hafiz Majid	Universiti Sains Malaysia	2012–	Molecular phylogenetics and control of urban insect pests in Malaysia
Farkhanda Manzoor	Lahore College for Women University (Pakistan)	2004–	Termite control in Pakistan
Joe Mauldin	USDA Forest Service	1969–1989	Biology and control of wood-destroying insects, termiticide testing
Michael Merchant	Texas A&M University	1989–2020	Extension, biology, and control of urban insect pests
Matthew Messenger	New Orleans Mosquito, Termite and Rodent Control Board; USDA Animal & Plant Health Inspection Service	2000–	Area-wide termite baiting in Louisiana
Dini Miller	Virginia Tech	1998–	Assessment-based pest management of the German cockroach, bed bug biology and control
Peter Miller	University of Technology, Sydney, Australia	1977–2009	Development and testing of urban pest products in Australia
Jianchu Mo	Zhejiang University, China	1997–	Biology and control of subterranean termites in China
Harry Moore	NCSU	1964–1994	Biology and control of wood-destroying insects
Gabi Mueller	Urban Pest Advisory Service, Zurich (Switzerland)	1997–	Urban pest monitoring and control in Switzerland
Timothy Myles	City of Guelph, Ontario (Canada)	1984–	Termite biology and control
Kok-Boon Neoh	Universiti Sains Malaysia; Kyoto University; National Chung Hsing University, Taiwan	2009–	Cockroach biology and control in Taiwan, termite biology and control in Southeast Asia

(*Continued*)

Table 2 (*Continued*)

Researcher	Affiliation	Years active[a]	Research areas and notable contributions
William Nutting	University of Arizona	1964–1992	Biology of termites in the desert in the Southwest United States
David Oi	USDA ARS	1993–	Biological control of red imported fire ant and IPM strategies on pest ants
Faith Oi	University of Florida	2004–	Extension and control of structural and household pests
John Osmun	Purdue University	1948–1987	Formation of Pi Chi Omega, leadership in pest management industry
Richard Patterson	USDA ARS	1977–1998	Biology and control of cockroaches and cat fleas
Roy Pence	University of California, Los Angeles	1950–1975	Effect of sand particle size in preventing penetration of subterranean termite, alternative pest control
Roberto Pereira	USDA ARS, University of Florida	1993–	Biology and control of urban insect pests (pest ants, cockroaches, flies, bed bugs, etc.)
Bryce Peters	University of Technology, Sydney, Australia	1981–2018	Development and testing of urban pest products in Australia
Michael Potter	University of Kentucky	1990–2020	Extension and control of termites and bed bugs
Sanford Porter	USDA ARS	1989–2017	Biological control of red imported fire ant.
Reiner Pospischil	Bayer (Germany)	1982–2010	Development of control strategies against urban pests
Robert Puckett	Texas A&M University	2014–	Biology and control of fire ants & termites
Donald Reierson	University of California, Riverside	1962–2013	Biology and control of cockroaches, termites, ants, and yellowjackets
František Rettich	National Institute of Public Health, Czech Republic	1971–	Mosquito control in Czech Republic
Colette Rivault	Université de Rennes I, France	1976–2016	Cockroach behavior
William Robinson	Virginia Tech	1970–1996	Cockroach IPM, insecticide application, NCUE, ICUP
Alvaro Romero	New Mexico State University	2007–	Biology and control of bed bugs and Turkestan cockroach
Mary Ross	Virginia Tech	1959–2000	German cockroach genetics, glucose aversion
Michael Rust	University of California, Riverside	1975–	Biology and control of cockroaches, termites, ants, cat fleas, and yellowjackets; insecticide runs-off in urban settings
Coby Schal	Rutgers University, NCSU	1983–	Biology and management of cockroaches and bed bugs utilizing integrative approaches
Michael Scharf	Purdue University, University of Florida	1994–	Toxicology and molecular physiology of cockroaches, termites, pest ants, and bed bugs
Rudolf Scheffrahn	University of Florida	1983–	Systematics, biology, and control of termites
Khoirul Himmi Setiawan	Kyoto University, National Research and Innovation Agency (Indonesia)	2011–	Biology and control of drywood termites
Jules Silverman	American Cyanamid, Clorox, NCSU	1981–2021	Glucose aversion in German cockroaches, ecology and control of pest ants and cat fleas

(*Continued*)

Table 2 (*Continued*)

Researcher	Affiliation	Years active[a]	Research areas and notable contributions
Beverly Sparks	Texas A&M University, University of Georgia	1983–2014	Extension and control of urban landscape pests
William Spink	Louisiana State University	1958–1975	Insecticide resistance in German cockroaches, biology and foraging of Formosan subterranean termites
Vaclav Stejskal	Crop Research Institute, Czech Republic	1992–	Urban pests of stored products and their control
Nan-Yao Su	University of Florida	1983–	Termite ecology, behavior, and baiting
Daniel Suiter	Purdue University, University of Georgia	1994–	Extension and research program on the control of structural and household pests
Qian Sun	Louisiana State University	2013–	Behavior and evolution of social insects, chemical ecology
Andrew Sutherland	University of California Cooperative Extension	2012–	Extension; IPM strategies against cockroaches, bed bugs, and termites in California
Yuichiro Tabaru	Fuji Environmental Service Co., Ltd. Japan	1974–2015	Biology and control of cockroaches
Minoru Tamashiro	University of Hawaii	1959–1989	Biology of termites, physical termite barriers
Siavash Taravati	University of California Cooperative Extension	2017–	Extension; IPM strategies against cockroaches, bed bugs, and termites in California
Jia-Wei Tay	University of California, Riverside; University of Hawaii	2014–	Biodegradable hydrogel bait, biology and control of invasive urban pests of Hawaii
Ellen Thoms	Dow AgroSciences, Douglas Products	1986–2020	Termite control, fumigation
Barbara Thorne	University of Maryland	1994–2021	Biology, evolution, genetics, and behavioral ecology of termites
Hideakira Tsuji	Sankyo Co., Ltd (Japan); KSK Institute for Environmental Biology (Japan)	1965–2020	Cockroach biology and control
Kunio Tsunoda	Kyoto University	1995–2011	Termite biology and control, wood preservatives
Karen Vail	University of Tennessee	1994–	Extension and IPM strategies of urban insect pests
Steve Valles	USDA ARS	1994–	RNA viruses against red imported fire ant, insecticide resistance in German cockroaches
Robert Vander Meer	USDA ARS	1977–	Development of controlled release toxicants against red imported fire ant, chemical ecology
Edward Vargo	NCSU, Texas A&M University	1986–	Molecular ecology of urban pests, biology of social insect pests
G. Veera Singham	Universiti Sains Malaysia	2012–	Molecular phylogenetics of urban insect pests, insecticide resistance
Richard Vetter	University of California, Riverside	1995–2012	Biology and control of urban spiders, yellowjackets, and ants
Bradley Vinson	Texas A&M University	1969–2016	Behavior and physiology of red imported fire ant and solitary bees

(*Continued*)

Table 2 (*Continued*)

Researcher	Affiliation	Years active[a]	Research areas and notable contributions
Charunee Vongkaluang	Royal Forest Department, Thailand	1978–2013	Ecology and control of termites in Thailand
Robert Wagner	University of California, Riverside	1959–1983	Biology and control of yellowjackets and ants
Changlu Wang	Purdue University, Rutgers University	2002–	IPM strategies against cockroaches, bed bugs, and mice
Herbert Weidner	Zoological Museum Hamburg	1937–1979	Biology and control of wood-destroying insects
David Williams	USDA ARS	1981–2004	Biology and control of the red imported fire ant
Eugene Wood	University of Maryland	1968–1988	Insecticide resistance, IPM
Charles Wright	NCSU	1963–1995	Crack and crevices treatment, insecticide movement from structures and vehicles to nontarget sites
Wen-Jer Wu	National Taiwan University	1992–2020	Biology and control of the cat flea and red imported fire ant in Taiwan
Yi-Juan Xu	South China Agricultural University	2007–	Biology and control of red imported fire ants and termites in China
Chin-Cheng Scotty Yang	National Taiwan University, Kyoto University, Virginia Tech	2011–	Molecular ecology of pest ants, insect–microbial interactions
Han-Heng Yap	Universiti Sains Malaysia	1972–2003	Biology and control of household insect pests
Tsuyoshi Yoshimura	Kyoto University	1994–2021	Biology and control of wood-destroying insects, termites, and wood-boring beetles
Julian Yates III	University of Hawaii	1975–2016	Biology and control of termites in Hawaii
Patricia Zungoli	Clemson University	1981–2017	Biology and control of cockroaches, termites, and ants; NCUE

[a]Refers to the years active in urban entomology research.
Many of the researchers listed are either personally known to the authors or cited in this review. Abbreviations: ARS, Agricultural Research Service; CSIRO, Commonwealth Scientific and Industrial Research Organization; ICUP, International Conference on Urban Pests; IPM, integrated pest management; NCSU, North Carolina State University; NCUE, National Conference on Urban Entomology; USDA, United States Department of Agriculture; Virginia Tech, Virginia Polytechnic Institute and State University.

in the tropics and subtropics, while *C. lectularius* is more prevalent in temperate and subtropical areas (19, 20). Almost all populations of both species investigated have been found to be resistant to different classes of insecticides, especially to pyrethroids (15). The resurgence of these two species stimulated basic and applied research and development of intensive pest management. From 1896 to 2000, approximately 277 research papers and articles were published on bed bugs; between 2001 and 2022, 890 papers were published (for the most up-to-date numbers, see **https://pubmed.ncbi.nlm.nih.gov/?term=cimex**).

3.4. Professional Pest Management Industry

The structural pest control industry and the professional pest management industry in the United States have their origins in the 1930s. Snetsinger (88) traces the early beginnings of these industries and the emerging cooperation between them and the science community. By 1965, the annual revenue from 6,000 pest control firms was approximately $350 million (equivalent to $3.3 billion in 2022) (68). In 2022, the structural pest control market in the United States surpassed $11 billion (25, 71). Over the past 50 years in the United States, the control of general pests such as ants,

cockroaches, fleas, flies, and termites generated approximately 75% of the income and revenue of these industries (1, 3, 29, 64).

Urban entomology was not the main emphasis of entomologists in Asia until after the 1960s. Most of the insect-related problems that affected humans at that time were vector-borne diseases. Due to limited resources, funding went to research on the vectors of malaria, filariasis, and dengue. The bed bug was the first urban insect pest of significant concern to the people in this region. This pest has affected people in Asia for hundreds of years (57). In the 1940s, the bed bug was one of the targeted pests of Japanese pest control operators in Tokyo (48). In China, the Four Pests (rodents, bed bugs, flies, and mosquitoes) were targeted in a nationwide elimination campaign in 1960 (10). Trained personnel were deployed throughout the country to conduct surveys and demonstrate treatments, and residents were provided insecticides with which to carry out the control (57). In 1978, a National Four-Pest Elimination Research Cockroach and Bed Bug Working Team was formed to research cockroach and bed bug infestation, with a particular focus on monitoring, control, and pest biology (103).

In the United States, the Federal Insecticide, Fungicide, and Rodenticide Act was enacted in 1947 and amended in 1972. It transferred the regulatory responsibilities to the newly established Environmental Protection Agency (EPA). Amendments to this legislation required private and commercial pesticide applicators to be certified as competent to apply pesticides. Initial certification was followed by requirements for continued training related to research and development in urban entomology and integrated pest management (IPM) strategies and practices (88). This continuing education requirement (called recertification) encouraged the professional pest management industry to join with federal and state regulatory agencies to develop standards for training. For example, in Indiana, the continuing certification for PMPs began in 1977. PMPs had the option of renewing certification by retesting or through continuing education programs. This encouraged certified commercial applicators to update and increase levels of professional competency while attaining certification renewal. The training requirement was primarily the responsibility of the Cooperative Extension Service, the educational component of land grant universities. This meant hiring additional personnel and faculty. This would be repeated throughout the other states. The importance of the land grant institutions is evident from a 1977 survey of 351 PMPs, primarily owners and directors, that revealed that 47.6% relied on extension agencies and 39.9% relied on university sources for answers to technical problems (1).

Private consultants and industry spokespersons provided training materials, courses, and extension-related activities beginning in the 1960s. Some of the consultants included Paul Adams, Jim Ballard, Judy Black, Bobby Corrigan, Jim Fredericks, Austin Frishman, Ted Granovsky, Ralph Heal, Stoy Hedges, Richard Kramer, Doug Mampe, David Mueller, George Rambo, Phil Spear, and Jeff Tucker (4). They provided some of the early training programs for the structural pest control industry. Outside the United States, Clive Boase (United Kingdom), Motokazu Hirao (Japan), Partho Dhang (Philippines), and David Mora del Pozo (Spain) provided training in the management of household and structural pests.

Resources within the land grant universities to conduct applied agricultural, medical, veterinary, and urban entomological research and provide extension programs have been declining over the past decades. The establishment of endowed positions (chairs) in university departments to promote the study of urban entomology and extension-related activities has been a meaningful contribution from professional pest control and related industries. These positions help establish permanent faculty positions and dedicated research positions that enhance the discipline of urban entomology and support professional pest management. The current positions include one at Texas A&M University (established in 1989); two at North Carolina State University (1993, 1999); one at the University of Florida (1999); one at Oklahoma State University (2001); two at

Purdue University (2010, 2020); one at the University of California, Riverside (2019); and one at Virginia Polytechnic Institute and State University (2023).

3.5. Land Grant Institutions

Land grant universities were essential to the development of urban entomology in the United States. These institutions were established in 1862 to support training and promote practical education related to agriculture, military tactics, and the mechanical arts (5). To carry out this mission, agricultural experiment stations and cooperative extensions were created in most states. The resources and facilities needed to conduct urban research and outreach were available when the discipline of urban entomology emerged in the 1970s.

The recognition of the need for cooperative extension programs and academic positions for research on household and structural pests and interaction with professional pest control began in the 1970s. The earliest programs included those at Purdue University; University of California, Riverside; Virginia Polytechnic Institute and State University; North Carolina State University; and the University of Nebraska. Many of the scientists contributing to the research base and extension programs were hired in the following 50 years (4) (**Table 2**). A contributing factor to this increase in urban positions was the retirement of faculty and specialists hired after World War II and the availability of these positions when urban entomology was expanding.

Universities offering undergraduate and graduate degrees with training or specialization in urban entomology include Clemson University; the University of California, Riverside; Ohio State University; Purdue University; Texas A&M University; the University of Florida; and the University of Missouri. Internationally, universities providing such training or specialization include Universiti Sains Malaysia and Zhejiang University (China). At other universities, the training of urban entomologists is typically part of agriculture pest management programs.

In recent years, the number of academic and cooperative extension programs in urban entomology has been reduced as retired faculty are not replaced (65) (see **Table 2**). The pest control industry has supported shared professorships at a few universities. However, these positions are primarily research positions, which require securing competitive grants to earn tenure and promotion. There has been little support for applied urban research and extension programs (79, 80).

3.6. Entomological Organizations

The International Congress of Entomology (ICE) was first convened in 1910 (77) with meetings organized around specific subject sections reflecting the broad scope of entomology at the time. In 1948, the sections dealing with economic entomology included Insects of Agriculture and Olericulture, Stored-Product Insects, and Means and Methods of Fighting Vermin. The section for stored product insects was changed to Stored Product and Industrial Insects (1964) and, later, Stored Products and Structural Insects (1976, 1980, 1988). As early as 1964, organizers of ICE recognized a difference between pests of stored products and those of urban environments. There were few papers submitted to the section for non–stored product insects prior to 1992. In 1992, the section was retitled Stored Product and Urban Entomology, and it continues with this title to the present day.

In 1960, a symposium was presented at the Vienna ICE titled "Insektenleben in der Großstadt (Großstadtbiologie)" (Insect Life in the Large City) (77). It included presentations on stored product pests in ports, insect pests of trees in Amsterdam, and an arthropod survey of Hamburg. One presenter, H. Kemper, was an early advocate of providing training for pest control operators in Germany (7) (**Table 2**). Unfortunately, many of his books and papers dealing

with urban pests have been lost. In 1960, no one referred to this symposium as dealing with urban entomology, and no other symposia were offered for the next 16 years. A symposium titled "Insect Impact on the Quality of Forest and Urban Environments" was presented in the Forest Entomology Section of the Washington, D.C. ICE in 1976.

The Entomological Society of America (ESA) is the largest professional organization devoted to studying insects, with more than 7,000 members. The society currently organizes its membership into four sections that closely reflect the members' interests: Medical, Urban, & Veterinary Entomology; Physiology, Biochemistry & Toxicology; Plant-Insect Ecosystems; and Systematics, Evolution & Biodiversity. Before 1986, many members in the field of urban entomology would have been affiliated with the Medical and Veterinary Entomology section. In 1986, the governing board was petitioned to elevate the status of urban entomology within the ESA. The governing board granted formal conference status to the urban entomology group (2). In 1995, urban entomology became the subsection Crop and Urban Pest Management and held its first meeting. With subsection status, formal symposia and paper presentation sessions were offered at the national ESA meetings. In 2008, urban entomology was combined with medical and veterinary entomology to form the section Structural, Veterinary, and Public Health Systems. Full recognition occurred in 2010, when the sections within ESA were reorganized to include Medical, Urban & Veterinary Entomology.

The discipline of urban entomology gained national and international recognition from two research-based conferences. The National Conference on Urban Entomology held its first meeting in 1986. The field of urban entomology had been growing for approximately 10 years, and there was an active research base. Name recognition for urban entomology was critical for maintaining industry and academic support. The Conference grew steadily and within two years had regular international participants and presentations. This Conference is held every two years. The papers from the presentations from these conferences are available online (**https://ncue.tamu.edu/proceedings**).

The first International Conference on Urban Pests (ICUP), originally the International Conference on Insect Pests in the Urban Environment, was held in 1993 at Cambridge University, United Kingdom. Participation was worldwide, which further strengthened the discipline with an increased level of international recognition. The permanent ICUP website (**http://icup.org.uk**) maintains a database of the proceedings of all 10 conferences. It is the largest free-to-access online database on urban entomology. The current database has more than 1,300 documents. This feature of the ICUP further strengthens the urban entomology community worldwide and is a stimulus for international researchers to attend and present their work.

Pi Chi Omega is an organization of professionally trained entomologists interested in structural pest control. It was established in 1950 on the campus of Purdue University (30) and now has international members. Its mission is to connect and enrich the pest management community and provide leadership that will promote urban entomology and urban entomologists and support the extension aspects of IPM. Pi Chi Omega is also addressing the recruitment and retention of students into urban and structural entomology, with the goal of involving these students in sound academic and internship activities. Six perpetual scholarships have been established for students training in urban entomology.

3.7. University Conferences

The professional pest control industry and land grant universities cooperated in developing training programs and conferences. Under the leadership of J.J. Davis, the Purdue University Annual Pest Control Conference was first held in 1937 as a joint project by the Purdue Entomology Department and the National Association of Exterminators and Fumigators (changed to the

National Pest Control Association in 1937) (88). They aimed to provide PMPs with the latest technologies and advances in urban pest control and household and structural pest control. This would ultimately provide consumers with a more competent pest control service. This was the first educational conference for the industry, and 78 participants from 14 states attended. When the EPA and most states began requiring continuing education for PMPs, the Purdue conference was expanded.

The Eastern Regional Pest Control Conference was the combined effort of the National Pest Control Association and the University of Massachusetts (88). The first conference was held in 1941, and conferences continued until 1972.

In the 1950s, pest control companies had few training opportunities regarding the chemicals used and how they could be applied safely and effectively. An annual state conference with the Department of Entomology at North Carolina State College (North Carolina State University) was initiated in 1951 as a two-day short course called Pest Control Operators School. The primary goal of the short course was to improve the quality of services that the industry provided by increasing PMPs' understanding of pest biology, available pesticides, and new application methods and equipment. Another goal was to foster discussion and cooperation in setting new standards of ethics for the industry, leading to the formation of the North Carolina Pest Control Association. This early conference evolved into a four-day conference, which is now called the North Carolina Pest Management Association Pest Control Technician School.

These early conferences became the model for conferences held in many other US states later.

4. FUTURE SUPPORT AND DIRECTIONS

Support for research and extension programs has always been an issue for those in urban entomology (79, 80). This discipline does not fit within the framework of the 2018–2020 USDA Agricultural Research Service objectives of Transforming Agriculture (USDA), and competition for USDA funding is intensive (100). Alternative state and federal funding sources independent of agriculture are needed. The pest control industry is an important contributor to research and extension programs. Mergers and consolidation in the industry reduce support in the future. As the costs of conducting basic and applied research and extension programs increase, new sources of financial support and recognition are needed. Cooperation between the professional pest control industry and land grant institutions will be vital in securing state and federal funding.

What will happen to urban entomology at universities in which Departments of Entomology have merged with other disciplines such as nematology, plant pathology, and environmental sciences? Departmental mergers have occurred at the University of California, Berkeley; Auburn University; the University of Hawaii; Clemson University; North Carolina State University; Oklahoma State University; and the University of Tennessee. When university-based urban entomologists retire, positions are reallocated to other disciplines. Endowed positions can be reimagined and redirected without any level of intervention by the pest management industry, even from those who have been involved in creating and funding the position. Industry leaders will need to interact with deans and directors at land-grant institutions and organizations such as the Association of Public and Land-Grant Universities and National Extension Directors and Administrators to advance urban entomology. Industry leaders and urban entomologists must step forward and advocate to ensure that research, teaching, and extension programs continue to serve the pest management industry and the stakeholders that they serve.

The future agenda in urban entomology will include issues such as physiological and behavioral resistance to pesticides, invasive species, climate change impacts on urban pests, and training and certification of PMPs. Over the past decade, there has been an increased awareness of the role of urban pest management methods and the runoff of pesticides in urban waterways (31). New

low-impact pest control strategies are needed to address these issues. Physiological and behavioral resistance in bed bugs and cockroaches disrupt pest management programs for these pests. The use of molecular techniques and new technologies will be critical to resolving these issues.

Cooperation and connections with researchers in developing nations will be crucial as invasive urban pests from tropical regions invade temperate zones. With the advancement of transportation systems, geographical barriers between countries are being reduced, and the invasions of urban pest species from different regions of the world will become increasingly common. Intermodalism allows products to be shipped around the world quickly, cheaply, and efficiently by using cargo containers that more easily fit on trucks, trains, and ships, making it easier for invasive insect pests to spread across continents and oceans (66). The global trade of goods and commodities is a major driver of the spread of invasive urban insects. These insects can also be transported through the movement of people, whether it be in luggage or on clothing. The introductions of the red imported fire ant to Australia, China, Japan, and Korea provide a good example of how trade facilitates the spread of invasive species. As the climate changes, urban centers will also undergo changes that increase the likelihood of new invasive pests. Better detection and interdiction strategies are needed.

SUMMARY POINTS

1. The publication of *Urban Entomology* in 1975 was a catalyst for the developing discipline of urban entomology.
2. Interaction between the structural pest control industry and land grant universities provided the impetus for the emergence of urban entomology in the United States.
3. Increased urbanization, invasive urban pests, and increased demand for pest control services contributed to the development of urban entomology programs worldwide.
4. Regulatory changes in the 1970s required additional training and certification of pest management professionals, stimulating urban entomology research and cooperative extension at universities.
5. The discipline of urban entomology gained national recognition by the 1990s and international recognition in the proceeding decade.
6. Pest problems associated with urbanization will continue to increase, especially in the tropics and developing countries.
7. Retention of positions devoted to urban research and extension is a significant challenge as universities reconfigure themselves.
8. Funding and support for urban entomology will become an issue in the next decade unless new sources are found.

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