Integrated Pest Management Reviews **4:** 53–73, 1999.

Poultry integrated pest management: Status and future

Richard C. Axtell*
*Department of Entomology, North Carolina State University, Raleigh, NC 27695-7613 USA; *Address for correspondence (3427 Churchill Road, Raleigh, NC 27607-6809 USA; Tel.: 919-787-1321 or 919-781-2499; Fax: 919-515-7746 or 919-781-2499; E-mail: richard_axtell@ncsu.edu)*

Received 9 August 1998; accepted 26 November 1998

Key words: poultry pests, integrated pest management, poultry ectoparasites, muscoid flies, filth flies, manure arthropods, rodents

Abstract

Modern commercial poultry production under large companies is expanding worldwide with similar methods and housing, and the accompanying arthropod and rodent pest problems. The pests increase the cost of production and are factors in the spread of avian diseases. The biology, behavior and control of ectoparasites and premise pests are described in relation to the different housing and production practices for broiler breeders, turkey breeders, growout (broilers and turkeys), caged-layers, and pullets. Ectoparasites include *Ornithonyssus* fowl mites, *Dermanyssus* chicken mites, lice, bedbugs, fleas, and argasid fowl ticks. Premise pests include *Alphitobius* darkling beetles, *Dermestes* hide beetles, the house fly and several related filth fly species, calliphorid blow flies, moths, cockroaches, and rodents. Populations of these pests are largely determined by the housing, waste, and flock management practices. An integrated pest management (IPM) approach, tailored to the different production systems, is required for satisfactory poultry pest control. Biosecurity, preventing the introduction of pests and diseases into a facility, is critical. Poultry IPM, based on pest identification, pest population monitoring, and methods of cultural, biological, and chemical control, is elucidated. The structure of the sophisticated, highly integrated poultry industry provides a situation conducive to refinement and wider implementation of IPM.

Introduction

Commercial poultry production is rapidly expanding worldwide to meet the needs of the increasing human population. Per capita poultry meat consumption is increasing with the reduced cost and enhanced incomes. This large poultry industry requires extensive housing for the birds and produces large quantities of wastes (manure, used litter, dead birds) which present ample habitats for the development of arthropod and rodent pests. The industry has been growing at 4–5% per year and is expected to continue expansion in the foreseeable future. Effective pest management is a significant part of the poultry industry operational needs.

The magnitude of the poultry industry is impressive (1997 data from U.S. Government, 1998). The worldwide total of all types of poultry meat production (ready-to-cook equivalents) is about 52 million metric tons. The percentages of the world total by regions and major producing countries are: North America 33.2 (United States 28.3), South America 12.3 (mainly Brazil 8.6), European Union 15.7 (France 4.3, United Kingdom 2.8, Italy 2.2, Spain 1.8), Eastern Europe 1.8, Russia and Ukraine 1.6, Middle East 2.4 (mainly Saudi Arabia and Turkey), Africa 2.4 (mainly Egypt and Republic of South Africa), and Asia 29.5 (People's Republic of China 21.8, Japan 2.3, Thailand 1.8). The bulk of poultry meat production is broiler chickens with the total broiler meat production worldwide being about 37 million metric tons. The percentages of the world total broiler production by regions and major producing countries are: North America 39.2 (United

States 33.1), South America 15.6 (mainly Brazil 12.0), European Union 15.4 (France 3.2, United Kingdom 2.9, Spain 2.4, Italy 1.8, Netherlands 1.7), Eastern Europe 1.6, Russia and Ukraine 1.1, Middle East 1.7 (mainly Saudi Arabia), Africa 2.7 (mainly Egypt and Republic of South Africa), and Asia 21.3 (People's Republic of China 15.5, Japan 3.0, Thailand 2.4). There are an estimated 24 billion broiler chickens raised each year in the world; about 8 billion in the United States. Turkey meat production worldwide is about 4.6 million metric tons with most of the production in the United States (53.1%) and the European Union (36.8%).

Egg production in the world is about 707 billion per year. This requires about 2.8 billion laying hens. The percentages of world total egg production by regions and major producing countries are: North America 15.6 (United States 11.0, Mexico 3.8), South America 2.8 (mainly Brazil 1.8), European Union 11.7 (France 2.3, Germany 2.0, Italy 1.7, United Kingdom 1.5, Netherlands 1.4, Spain 1.4), Eastern Europe 1.6, Russia and Ukraine 5.7, Middle East 1.3 (mainly Turkey), and Asia 61.2 (People's Republic of China 47.5, Japan 6.1, India 4.2).

The modern poultry production systems are large operations, using high densities of animals, financed and managed by large companies. These production management systems are highly structured and sophisticated, and under the control of a parent company ('integrator') who owns the feed mills, hatcheries, processing plants, transportation, and some of the poultry houses. The integrator contracts with individual producers ('growers') who raise the poultry, with the young birds and feed supplied by the integrator. The contract producer usually supplies the poultry houses, utilities and labor. The producer is paid on a per unit basis (number of eggs, weight of birds) and has to follow the instructions of the integrator who employes veterinarians and technical personnel (service persons) who routinely inspect the flocks and records of the contract producers. With such large scale operations, even very small losses due to pest and disease problems have a large economic impact on the integrator and the contract producer. The threat of arthropod and rodent pests is serious and control of these pests requires an integrated pest management (IPM) approach consistent with the sophisticated poultry production systems and management strategies.

The objective of this paper is to describe important poultry pests and principles of their management in relation to modern, large-scale commercial poultry production systems. The intent is to synthesize current knowledge based not only on the extensive literature but also on the author's observations and experience gained from research and interacting with other entomologists and persons in the poultry industry since the 1960s. The reader should refer to Axtell and Arends (1990) for a review of arthropods associated with poultry which contains an extensive list of references. Further information and references on poultry pests and diseases are provided by Calnek et al. (1991) and Williams et al. (1985).

Production systems

Modern commercial poultry production uses fully integrated production techniques that allow for the production of a large number of eggs, or birds for meat, on a small amount of land. This change from old small flock, low bird densities to large flock, high bird densities has completely changed the environment in which the birds are reared and in the stressors that can alter growth and production. In these high density production systems, management of the arthropod pests is directly related to the type of product being produced (meat or eggs), housing type, feed and water equipment, manure disposal, and the environmental quality within the houses. For each type of poultry being produced, there are specific requirements for temperature, air quality and movement, feed, and housing for maximum production at the least cost. The pest populations are related to the flock management and production practices and any pest management strategies must be compatible with the poultry production requirements.

The ecology of the pests is tied to the artificial environment in which they and the birds exist, and changes in the environment that impact pests can be made only if they are not detrimental to the birds. Because the environment of the various types of production facilities differ, the complex of pests differs among the systems. As examples, flies (the house fly and related filth flies) are a major problem in caged-layer and breeder houses but usually not a problem in broiler facilities; northern fowl mites are a problem on the birds in caged-layer and breeder flocks but are rare in broilers which are in a house for too short a time (7–8 weeks) for a detrimental mite population to develop. Although the details vary to meet climatic and geographic needs, the facilities and techniques for modern poultry production are very similar worldwide. For further information on poultry production consult North and Bell (1990) and Parkhurst and Mountney (1988).

In relation to pest management, five categories of facilities and production systems for chickens and turkeys are important: broiler-breeders, turkey-breeders, growout (broilers and turkeys), caged-layers, and pullets (caged and floor-grown).

Broiler breeders

Broiler breeders or ‘heavy breeders’ are chickens that are managed for the production of fertile hatching eggs with the offspring being broiler chicks. The breeder birds are genetically selected to produce fast growing offspring (broilers that reach 2.2 kg in 45–50 days). Male and female adult broiler breeders (in a 1 : 10 or 1 : 12 ratio) are maintained in flocks of 4,000–8,000 in one-story houses (12–19 m by 120–180 m) at densities of about 5 birds per sq. m. The house usually has the middle one-third of the floor (dirt or concrete) covered with litter (wood shavings or other absorbent material) and raised slats along the outer one-third of each side of the house. The slat area consists of narrow wood strips elevated 0.5–0.75 m above the floor. The automatic water and feed equipment are on top of the slats which encourages the birds to defecate while on the slats resulting in manure accumulating beneath the slats for the duration of the flock. Eggs are laid in nest boxes arranged along the edge of the slatted areas. The eggs are collected by hand or an automatic belt system. With hand collection, the boxes contain some wood shavings or a tufted plastic floor; with the automatic system the boxes have an inclined floor pad and a fabric collecting belt. The breeder house environment is regulated by circulating air with fans and there may be closed sides with adjustable vents or open sides with adjustable curtains to provide natural ventilation.

Broiler breeders at 18–24 weeks of age are placed in the house and remain there for 9–12 months after which they are removed and the house thoroughly cleaned. The water and feed equipment, nest boxes and slats are removed and the inside of the house is washed and disinfected after removing the litter and manure. The house is empty for 3–6 weeks between flocks to allow time for cleaning and replacing equipment and litter.

Turkey breeders

Turkey breeders are maintained for the production of fertile turkey eggs to produce offspring to be grown to market weight. The female birds (hens) are maintained in groups of 1,500–2,000 per house (about 4 birds per sq. m) and the males (toms) in a separate adjacent house. The hens are artificially inseminated, usually once a week. Due to the large size of these genetically selected birds (females, 6.8–11.3 kg and males 15.8–25.0 kg), natural mating is inefficient and often injurious. The hens are allowed access to nests for only a short time daily and the eggs are collected frequently in order to prevent the hens from attempting to sit or ‘brood’ a clutch of eggs and cease further egg production. The groups of nest boxes rest on the floor and contain a layer of gravel or other appropriate material. Egg collection is usually by hand but there may be an automatic system with nest pads and collecting belt. The turkey house is one-story with litter on the dirt or concrete floor; there are no raised slates. The automatic water and feed equipment are suspended slightly above the litter in rows along the length of the house.

Growout (broilers and turkeys)

Broilers and turkeys produced for meat are usually raised to market weight in ‘growout’ houses (12–19 m by 92–184 m) on a dirt or concrete floor covered with litter (wood shavings, peanut hulls or other absorbent material). The house is one-story with adjustable curtains on the sides to allow control of air flow and temperature; alternatively the house may be closed with fans and vents to control ventilation. There are typically 12,000–25,000 broilers or 5,000–6,000 turkeys per house. Although the litter may be removed and the house cleaned between flocks, it is more common to use the same litter for several flocks prior to cleaning the house about once a year. Some new litter may be added between flocks after ‘decaking’ (removing areas of hard compacted litter or breaking up the litter with a tilling machine). These practices result in an accumulation of 15–20 cm of litter in the houses which fosters the buildup of arthropods in the litter. The automatic water and feed equipment are suspended slightly above the litter in several rows along the length of the house.

The 1-day-old broiler chicks are placed in the house and remain there until market weight (2.0–2.5 kg). The broiler chicks are usually confined in a portion of the growout house and provided with heaters for 1–2 weeks after which the temporary partitions are removed and the birds have access to the entire house (a practice called ‘partial brooding’). The broilers remain in a house for 42–55 days and a house can be used for 5–6 flocks per year. The young turkeys (poults) are segregated by sex and raised separately. They are usually raised in a separate brooder house for 4–5 weeks and then moved to a nearby growout house until they reach market weight (hens, 6.3–8.2 kg; toms, 13.6–18.1 kg). The turkey hens require 14–16 weeks to reach market weight; the toms 18–20 weeks. The practice of growing turkeys in outdoor lots has been largely abandoned, due partially to pest and disease problems.

There is beginning to be use of cage systems for broiler growout in some regions. In the caged systems, the birds have no contact with the floor and the houses are most often totally enclosed with fans and vents for control of air flow. There may be a belt system for removing the manure from beneath the cages. This arrangement is less favorable for the buildup of arthropod pests than the conventional growout system.

Caged-layers

Commercial layers are chickens housed for the production of eggs for eating or used in edible products. These birds are maintained in wire mesh cages in several different types of houses. Water and feed is provided to the cages by automatic equipment. Usually the feed line is in front of the cages and water is provided by cups or nipples attached to pipes running on top or behind the cages. The eggs roll out of the cages onto an automatic conveyer belt, although in some older houses the eggs may be collected by hand. The feces from the birds falls through the mesh bottom of the cages and accumulates on the floor or falls onto a conveyer belt which removes the manure to the end of the house. In the case of manure falling to the floor, the manure may be left to accumulate for weeks or months or it may be frequently removed by a scraper or water-flushing system.

The layers are placed in the cages as pullets (16–18 weeks old) and remain in the house for 12–18 months. Typically there are 3–4 birds per cage which is about 30 cm wide by 30 cm tall by 45 cm deep, although variations in dimensions are common. Other sizes of cages may be used including larger ‘colony cages’ with a wider front and containing more birds. To maximize the number of birds per house, the cages are usually arranged in stacks of 3–5 tiers of back-to-back cages attached to steel supports and arranged along the length of the house. The only access to the birds is from the front of the cages. There may be slanted plastic panels (dropping boards) between each tier of cages to deflect the feces and prevent them from falling on the birds in the lower cages. Most houses are wide enough for several rows of these stacked cages with narrow walkways between. A house may have open sides with movable curtains for regulating natural air flow or may be enclosed with fans and adjustable louvers and thermostats for temperature control. Houses may contain 50,000 or more birds with smaller houses holding 10,000–20,000. Several houses of caged layers may be grouped together in a complex containing as many as 5 million birds. The trend is for larger houses and larger complexes with on-site egg processing facilities owned and operated by a company rather than by a contract producer.

There are a variety of caged-layer housing types which may be categorized as (1) high-rise deep pit, and (2) one-story wide-span. The deep pit house is two-story with 30,000–100,000 birds in cages in the second story raised 3.6–5.5 m above the dirt or concrete floor of the first story. The manure accumulates for 2–4 years in the first-story and is removed with a tractor-mounted front-end loader. The wide-span houses have the cages 1.0–1.5 m above the floor (dirt or concrete). In some cases the manure is allowed to accumulate under the cages for several weeks or months and is removed by hand or with a tractor-mounted scoop. In other houses, the concrete floor has a 15–20 cm deep shallow pit beneath the rows of cages which is cleaned frequently by scraping or flushing. In the ‘scraper’ houses, the manure is moved to the end of the house daily by a scraper pulled by motor-driven cables; in the ‘flush’ houses, the manure is moved to the end of the house and to an outside lagoon daily by flushing the shallow pit with water pumped from the lagoon. The waste lagoons are usually deep and designed to break down the manure anaerobically and to be useable for many years. In some cases, the lagoons are shallow to allow more aerobic action to reduce odors.

Pullets

Pullets are replacement chickens grown from hatching to 16–24 weeks old when they are moved to broiler breeder or layer houses. The pullets are raised in a variety of housing types including litter-covered floor, wire mesh flooring, and cages. The same types of feeders, waterers, and manure disposal systems as described above are used according to the type of housing.

Poultry pests

The pests affecting poultry production may be categorized as (1) ectoparasites and (2) premise pests. The ectoparasites include mites, lice, bedbugs, fleas, and soft ticks. The premise pests include darkling beetles ('litter beetles'), flies, moths, cockroaches, and rodents (mice and rats). Rodent control is an important part of IPM although the emphasis of this paper is on arthropod pests. Arends (1991) describes rodent control in poultry facilities.

In order to visualize poultry IPM, it is necessary to examine the biology and control strategies for these pests in relation to the types of poultry management and housing. Modern commercial poultry production practices have resulted in exploding populations of many of these pests. What were minor pests in small flocks are now often major pests in high-density large production systems.

Ectoparasites

Mites

The northern fowl mite, *Ornithonyssus sylviarum* (Canestrini and Fanzago) [Acari: Macronyssidae], is the most common and widely spread ectoparasite (Hogsette et al. 1991, Lemke and Kissam 1986). In tropical areas the species may be replaced with the tropical fowl mite, *O. bursa* (Berlese), but the biology, behavior, and control measures are the same for both species of fowl mites. Fowl mites are common on chickens, turkeys, and all kinds of wild birds; the mites may accidentally occur on rodents but do not reproduce there. The entire life cycle of *Ornithonyssus* fowl mites is spent on the bird. The eggs are laid at the base of the feathers, especially in the vent area, and hatch into a minute six-legged stage (larva). This is followed by the eight-legged stages: protonymph, deutonymph, and adult. Only the protonymph and adult stages feed on the host. The protonymph feeds twice before molting. The adults feed repeatedly and lay several eggs after each blood meal. The life cycle is short (as few as 5 days) and large populations develop quickly on the birds. Although the entire life cycle is on the host, some later stages may wander off the host or be dislodged and can survive for at least a week thereby offering an opportunity for transmission. The sources of infestation in a flock are infested pullets, wild birds, contaminated workers, egg flats, and other equipment brought into the facility (Kells and Surgeoner 1996, 1997). Mite control depends on preventing these sources of introduction into a flock. When an infestation is found, chemical spraying with high pressure is the common practice. However, it is difficult to achieve control due to poor penetration of the feathers and a second application is necessary.

Fowl mites are often a problem in caged-layers, and breeder flocks. This reflects the type of housing and the length of time (9–18 months) the birds are in the house. Fowl mites are of little importance in broiler and turkey growout houses due primarily to the relatively short time the birds are in the house. In commercial caged-layers and broiler breeders, infestations are often the result of restocking with infested pullets and by visiting wild birds. The transport of contaminated egg cases from one farm to another is a source of infestation in the breeder flocks. Laying hens usually have the greatest mite infestation in the vent region while the infestation is more widely spread on roosters. In broiler breeder flocks, infested roosters spread the infestation among the hens. In turkey breeder flocks, mite transmission from the separate toms to the hens may be by contaminated workers involved in the insemination process. The infestation in the turkey breeder hens is likely to be due to using infested poults and wild birds visiting the houses.

The second type of mites affecting poultry production are in the genus *Dermanyssus* [Acari: Dermanyssidae] with *D. gallinae* (De Geer) the most important (Fletcher and Axtell 1991, Maurer and Baumgartner 1992). It is known as the chicken mite, red mite, and roost mite. The chicken mite biology is very different from that of fowl mites. The chicken mite is on the bird only to feed (mostly at night) and spends the rest of the time concealed in cracks and crevices and litter. Its eggs are laid in the hiding places and hatch into six-legged larvae in 2–3 days. The larvae molt into eight-legged nymphs without feeding. The two nymphal stages and adults feed on the birds intermittently. The adults are able to live off the host without feeding for up to 34 weeks. The temperature in the habitat used by the life stages of the mite largely determine the length of time required to complete the life cycle from egg to adult. Overall, the chicken mites are likely to complete a life cycle in a poultry house in about 2 weeks. The chicken mite is seldom seen on the birds because of its intermittent feeding at night but skin lesions (especially on the breast and lower legs) are evidence of the feeding. The possibility of differences in behavior among strains of chicken mites is suggested by reports from Japan of the mites staying on chickens to feed and propagate even in the daytime (Nakamae et al. 1997a,b).

Dermanyssus chicken mites are likely to be a problem in poultry production systems which are favorable to the mite life cycle by providing easy bird access and ample hiding places. Therefore, chicken mites most often occur in broiler breeder houses; the litter, slats, and nest boxes provide excellent hiding places and easy access to the birds. Chicken mites may also be a problem in turkey breeder flocks. The mites may on occasions be a problem in broiler and turkey growout houses if the litter is not removed for several flocks. This results in plenty of hiding places and time for a significant mite population to develop. There is very little chance of a chicken mite infestation in caged-layer houses. However, changes in production systems to eliminate the cages for layers in Europe to meet animal welfare regulations is resulting in more cases of chicken mite infestations in layers (Hoglund et al. 1995).

Control of chicken mites depends on prevention of introduction. Because the mites live most of the time off the host, they may easily be transported from one farm to another by contaminated workers and equipment. Chicken mites are found on wild birds and may accidentally occur on rodents. When an infestation occurs in a house, it is necessary to spray not only the birds but the entire house and its contents; a second spraying is usually needed for effective control. More satisfactory control is achieved between flocks by total removal of litter and manure, cleaning the house and equipment, and spraying before restocking with birds known to be mite free. The limited number of effective, registered insecticides and the development of resistance by the mites are problems (Fletcher and Axtell 1991, Beugnet et al. 1997).

Lice

Several species of lice are known to infest poultry, but the most common and important in modern poultry production facilities is the chicken body louse, *Menacanthus stramineus* (Nitzsch) [Mallophaga: Menoponidae] (Price and Graham 1997). The entire life cycle occurs on the host (similar to fowl mites). The eggs are glued in dense clusters on the feathers. These masses of eggs are easily seen and may be especially common on the neck and thighs. The eggs hatch in 4–7 days into nymphs which rapidly develop through three instars to adult lice. The life cycle requires 2–3 weeks. The nymphs and adults move rapidly on the feathers and skin and are readily seen when the feathers are parted. The lice have biting and chewing (not sucking) mouthparts and their feeding leaves rough skin lesions. They also chew on feather barbs and barbules making the feathers less full and the habitat less favorable for fowl mites; usually fowl mite populations cannot coexist with chicken lice. Although several species of lice in other genera may be found on small ‘backyard’ flocks of poultry, those are apparently rare in modern commercial production systems (Arends 1991).

Chicken lice infestations are most commonly encountered in caged-layer flocks but may be a problem also in broiler breeder flocks. They are not likely to be found in broiler and turkey growout flocks due to the relatively short time the birds are housed. Infestations may be due to restocking with infested birds, introduction by wild birds, and transmission by contaminated workers and equipment. Rodents will harbor lice accidentally but are not a natural host. The common source of reinfestation in caged-layer houses is egg masses on broken feathers which are left in the house between flocks.

Control of lice infestations by spraying the birds is partially effective and a repeat spraying is required. For adequate lice control it is necessary to completely clean the houses between flocks and spray the house thoroughly. It is extremely important that all manure and feathers be removed to assure that some egg masses are not left behind.

Bedbugs

The bedbug, *Cimex lectularius* Linnaeus [Hemiptera: Cimicidae], is a blood-feeder attacking humans and poultry worldwide (Usinger 1966). In some tropical and subtropical areas it may be replaced with another species, *Cimex hemipterus* Fabricius. Bedbugs occur sporadically in modern poultry production facilities and an infestation of broiler breeder houses can be a serious problem causing reduced egg production.

Bedbugs, like chicken mites, are on the birds intermittently to feed (mostly at night). All stages of the bedbugs (eggs, five nymphal stages, and adults) are found concealed in cracks and crevices in the poultry house and especially in the slats and nest boxes in breeder houses. The eggs hatch in about 6 days and each of the five nymphal instars takes a blood meal. The adults feed many times. Bedbugs are very resistant to starvation; nymphs may survive without a blood meal for 70 days and adults can live without food for up to 12 months. When feeding, the bedbugs engorge rapidly (10 min or less). The night feeding bedbugs are rarely seen on the birds and can only be monitored by examining potential hiding places, looking for evidence of fecal spots (on posts, nest boxes, and other surfaces), and by the presence of lesions on the breast and legs of the birds.

Because the bedbugs spend nearly all of their lives off the host, development times depend on the house environment and the ability of the bedbugs to quickly obtain a blood meal which is not a problem with so many hosts conveniently nearby. Overall, the bedbugs are likely to complete a life cycle in a poultry house in about 4 weeks. They readily survive without food in the house between flocks making total elimination from a house very difficult. The ability of bedbugs to survive adverse conditions results in certain breeder houses being repeatedly infested in spite of attempts to control the insects. Similar to the situation with chicken mites, spraying the birds is not an adequate means of control. Control requires thorough cleaning of the house and equipment between flocks followed by insecticide application, although the number of effective and registered chemicals is limited (Fletcher and Axtell 1993).

Although data are limited, damage from bedbugs has been reported as allergic reaction of the growers, egg spots due to fecal deposits, lower production, and increased feed consumption. Poultry workers may be 'attacked' by hungry bedbugs and be inadvertently carried to the workers houses where a bedbug population might be established. Although bedbugs are normally nocturnal, after birds have been removed from an infested house for several days the insects may actively seek a host in the daylight.

Fleas

On rare occasions fleas [Siphonaptera] become abundant ectoparasites in poultry houses, mainly breeder and growout housing. The most common species are the cat flea, *Ctenocephalides felis* (Bouche), and the European chicken flea, *Ceratophyllus gallinae* (Schrank) (Cotton 1970, Dryden and Rust 1994). Even the human flea, *Pulex irritans* (Linnaeus), may be found infesting flocks. Fleas may be introduced into poultry houses by infested cats, rodents and wild birds. All of these species have the same basic life cycle. The adults blood feed on the host and lay their eggs which easily fall off the host. The habitat in the litter and nest boxes in breeder houses provides a suitable habitat for the eggs to hatch into larvae which develop through three instars (while feeding on organic matter) and form a pupae from which the adult flea emerges. The life cycle from egg to adult requires about 30 days depending on the habitat temperature and food supply for the larval stage.

These flea species should be easily seen moving rapidly through the feathers on the birds. Although the adult fleas prefer to stay on the host some will fall off and be found in the litter and nest boxes along with the larval stages and pupae. Control of a heavy flea infestation requires complete cleaning and spraying of the house and equipment as well as spraying the birds.

The sticktight flea, *Echidnophaga gallinacea* (Westwood), has a different behavior from the other flea species on poultry. It partially embeds in the skin of the bird, especially around the neck and head region. The flea eggs drop off the host into the habitat and develop in the same manner as the other flea species. The sticktight flea is cosmopolitan but rather uncommon in modern poultry production. Its biology is poorly known. Control is very difficult because the fleas are partially embedded on the birds and insecticide treatment of individual birds is necessary but usually not practical.

Ticks

Fowl ticks [Acari: Argasidae], *Argas persicus* (Oken) and *Argas radiatus* (Raillet), are frequently mentioned as poultry pests but are rare in modern poultry production. (Kohls et al. 1970). Wild birds may be a source of an infestation. Any infestation is most likely to be in breeder houses where the habitat is most compatible with the tick biology (similar to the situation with chicken mites and bedbugs). The fowl ticks feed intermittently on the birds and spend most of their time in the habitat. The stages in the life cycle are egg, larva (six-legged), two or three nymphal stages (eight-legged) and adult. The mobile stages feed on the blood of a bird for a few days at a time and then drop off into the litter or nesting material. The adults feed many times and continue to produce eggs at intervals after each feeding. The nymphs and adults can survive for several months without a blood meal. If an infestation occurs, control measures would be essentially the same as used for the chicken mite and bedbug.

Premise pests

Litter beetles

The major beetle pest infesting poultry litter and manure is the darkling beetle or 'lesser mealworm', *Alphitobius diaperinus* (Panzer) [Coleoptera: Tenebrionidae]. This worldwide pest reaches immense populations in litter in broiler breeder houses and growout houses as well as in the accumulated manure under caged layers and under the slats in breeder houses (Pfeiffer and Axtell 1980, Rueda and Axtell 1997). The beetle life cycle includes eggs, larvae (6–9 stages), pupae, and adults all of which are found in the litter or manure. A complete life cycle from egg to adult requires about 5 weeks, depending on the temperature (Rueda and Axtell 1996). The adults are extremely long-lived (at least a year) and able to survive adverse conditions. Some of the beetle larvae in the presence of dense populations move into the building insulation to pupate and in the process destroy the insulating value (Geden and Axtell 1987). Repair of damage to houses is costly and the reduced insulation interferes with bird production by making temperature control more difficult. In addition to this costly structural damage, the beetles are excellent reservoirs for disease organisms affecting both humans and birds and are a significant hazard to bird production (Jones et al. 1991a,b, McAllister et al. 1994, 1995, 1996). Young birds can eat large numbers of beetle larvae which interferes with normal feed consumption and growth and provides an avenue for disease transmission (Despins and Axtell 1994, 1995, Despins et al. 1994). Adult beetles are capable of flying and flight takes place mostly at night. When beetle infested litter is removed from poultry houses and spread on fields, the adults quickly leave the unsuitable habitat and fly to nearby human dwellings causing great annoyance and often lawsuits.

Control of the darkling beetle in the litter of growout houses is usually attempted by spraying the litter between flocks (Weaver 1996). In addition, treatment of the soil beneath the litter at the time of removal of old litter improves beetle control because many of the larvae burrow into the underlying soil to pupate. The popular practice of delaying removal of old litter to only once for every 4 or 5 broiler flocks to reduce the costs of production, has increased the beetle problem and made control more difficult. There are seldom attempts to control beetles in the manure under caged layers or under the slats in breeder houses because penetration by spraying would be inadequate and chemical treatment may kill the natural predators and parasites which suppress the pestiferous fly population (discussed later). Although the beetles tend to churn the manure and assist in drying and may even prey to a minor extent on fly larvae (Wallace et al. 1985), the detrimental characteristics of the beetles outweigh any benefits.

A second important pest species of beetles in poultry litter and manure is the hide beetle, *Dermestes maculatus* (De Geer) [Coleoptera: Dermestidae] (Jeffries 1980). This species is generally less abundant than the lesser mealworm in poultry houses but in some situations it, or a closely related species *D. lardarius* Linnaeus, may be a serious pest. This is especially true in high-rise, deep pit caged layer houses. The biology and behavior of the hide beetles is very similar to the lesser mealworm. The hide beetles not only bore into insulation but also into wood causing significant structural damage. All stages of the beetle (eggs, larvae [5–7 instars], pupae, and adults) are found in the litter and manure. The spilled poultry feed, supplemented by feathers and broken eggs, provides suitable nutrients for these beetles. The entire life cycle from egg to adult requires about 30–40 days. Effective control measures for hide beetles have not been developed although several insecticides are toxic and spray applications may yield some beetle population reduction.

Flies

Poultry manure which is moist is an ideal habitat for the development of large populations of the common house fly, *Musca domestica* Linnaeus [Diptera: Muscidae], and related species of ‘filth flies’ (Axtell 1986). Excessive numbers of the house fly and other filth flies in poultry facilities are unacceptable because the flies annoy workers, disperse to nearby residences and businesses (engendering disputes and lawsuits), and often constitute a violation of local public health laws and regulations. Flies are a reservoir and vector of a wide variety of pathogenic organism affecting humans as well as poultry. Also, the flies by defecation and regurgitation cause spotting on the structure and equipment, on light fixtures (reducing illumination levels), and on eggs (presenting potential for transmission of pathogens into the freshly laid egg).

The fly populations become greatest in the various types of caged-layer production systems and under the slats in broiler breeder houses. In those situations, accumulations of manure provides ample breeding habitat for flies. Even the scraper and flush systems of frequent manure removal under caged-layers may produce flies because the equipment leaves pockets of manure due to poor design or improper operation. In broiler and turkey growout houses, the litter is normally too dry for fly production but exceptions occur with wet areas around leaking water systems and high moisture levels in the litter due to rainwater draining into the houses. The longer birds are kept in a house to reach heavier market weights, the greater the risk of higher moisture levels and litter compaction leading to greater fly production.

House fly. The house fly is usually the most abundant and pestiferous fly species in poultry houses and it is the primary object of most fly management and control programs (Wilhoit et al. 1991a). Fly production is greatly influenced by manure quality, moisture, and temperature (Barnard and Geden 1993, Barnard et al. 1995, Fatchurochim et al. 1989, Wilhoit et al. 1991b). The life cycle usually requires about 6–10 days. The eggs are deposited in batches in the upper portions of manure having the most attractive odor and moisture levels. The eggs hatch quickly (less than 24 h) to first-stage larvae which subsequently molt into a second- and third-stage larvae. The larvae ('maggots') are near white, elongated, cylindrical and the largest last stage is readily seen in the manure. The late third-stage larva forms a pupal stage inside the altered larval integument (puparium). The puparium containing the pupa is oval, dark brown and immobile. It is readily seen. Pupation occurs in the drier portions of manure near the surface or edges. If pupae and third-instar larvae are present in the manure when it is removed and spread on fields, adult flies may emerge and disperse causing distress to neighboring homes and businesses.

Fannia *Flies.* Other muscoid flies common in poultry manure include several species in the genus *Fannia* [Diptera: Muscidae] (Skidmore 1985). The most widespread is *F. cannicularis* (Linnaeus), the 'little house fly', which may be a major pest in some regions. It is about one-half the size of the common house fly. This species often flies slowly in circles in the house, will disperse to neighbors, and may harbor human and avian disease organisms. This species has the same basic biology as the house fly but the larvae are different. The *Fannia* larvae are flattened, brown, and with numerous spiny projections; the pupae have a similar appearance. Development from egg to adult requires 15–30 days, a longer duration than for the house fly. Often *Fannia* larvae will be found in the manure along with house fly larvae. A few other species of *Fannia* with very similar appearance and behavior to the little house fly occur in poultry houses in some regions and are most readily distinguished by details of the arrangement and types of spines on the larvae.

Dump flies. Muscoid flies in the genus *Hydrotaea* (=*Ophyra*) [Diptera: Muscidae] are often called 'dump flies' or 'black garbage flies'. They are common in caged-layer and broiler breeder houses. The common species are *H. aenescens* (Wiedemann), *H. ignava* (Harris) [=*H. leucostoma* (Wiedemann)] and *H. capensis* (Wiedemann) (Adams 1984, Skidmore 1985). The adults are shiny black, slender, and about one-half the size of house flies. The larvae of dump flies are similar to house fly larvae but more slender and active. The dump fly larvae prey on small arthropods in the manure, including house fly larvae, and *H. aenescens* is sometimes promoted as a biological control agent against the house fly. Dump flies are often seen flying slowly in circles in a poultry house similar to the behavior of *Fannia* flies. In some cases of high populations, dump flies will be an annoyance to neighbors although the dump flies tend to disperse less readily than the house fly. Dump flies will leave fecal and regurgitation spots on the structure, light fixtures, equipment, and eggs in a manner similar to that of house flies.

Soldier fly. The black soldier fly, *Hermetia illucens* (Linnaeus) [Diptera: Stratiomyidae], is common in poultry manure worldwide and may be especially abundant in high-rise deep pit caged layer houses and under the slats in breeder houses (Shepard et al. 1994). The robust larvae churn the manure and physically render the habitat less suitable for the house fly and other muscoid flies. The solder fly oviposits egg masses on the drier portions of the manure. Larval development (5 instars) is slow (2 weeks or more) and the pupal stage lasts 2 weeks or more. A complete life cycle from egg to adult in poultry houses requires 40–60 days, and consequently larvae can become extremely abundant. Although these larvae discourage the development of the house fly and other muscoid flies, the larvae cause the manure to become liquified so that it is difficult to remove and may flow onto the walkways and undermine foundations of the houses. In breeder houses, the liquified manure may flow from beneath the slats and adhere to the feet of hens. The manure on the feet may adhere to the surface of the eggs as they are laid in the nest boxes and pathogens may enter the egg through the moist shell. Some pathogens transmitted in this manner can cause decreased hatch and chick growth.

Adult soldier flies are large, slender and slow flying. They may be found resting on vegetation around a poultry house as well as on the manure and surfaces in the house. They do not readily disperse in sufficient numbers to cause problems in nearby residences or businesses. Large numbers of the soldier fly larvae discourage house fly development and in rare circumstances the larvae have been observed to actually prey on other fly larvae. The use of soldier flies as a biological control agent against the house fly has been advocated. However, the disadvantages of soldier flies outweigh any benefits. Also, harvesting the larvae as fish bait and animal feed has been proposed.

Drosophila *flies.* Very small non-biting flies breeding in poultry manure may become a nuisance due to the large numbers. A common species worldwide is *Drosophila repleta* Wollaston [Diptera: Drosophilidae] which is dull brown and prefers the cooler areas of poultry houses for resting (Harrington and Axtell 1994). It is most abundant in caged-layer houses even if there is a flush or scraper manure removal system. Small accumulations of manure are sufficient for the development of large fly populations. The adults often congregate around the feed troughs and along the manure-crusted edges of the walkways. Invasion of the adjacent egg sorting and packing facilities causes annoyance to the workers. Several species of other small non-biting flies in the families Phoridae and Sphaeroceridae are also common in poultry manure.

Blow flies. Flies [Diptera] in the family Calliphoridae are commonly called ‘blow flies’. They lay their eggs on media rich in proteins (animal carcasses, broken eggs) where the larvae rapidly develop in less than a week to robust adults. Depending on the species, the adults are green, bronze, or black. Common genera associated with poultry production are *Lucilia* (=*Phaenicia*), *Phormia*, and *Calliphora*. Most blowflies result from improper disposal of dead birds in a poultry operation with very little production of those flies from manure. In caged-layer operations, defective egg handling equipment may result in broken eggs providing a place for blow fly development. The species *L. cuprina* (Wiedemann) and *L. sericata* (Meigen) are often associated with poultry and certain geographic strains are also known as ‘sheep blow flies’ due to their laying eggs and developing larvae in the soiled fleece of sheep (Stevens and Wall 1996, 1997).

Biting flies. All of the flies described above have sponging type mouthparts, do not pierce the skin and do not feed on the birds. Other flies which have piercing–sucking mouthparts and are able to take a blood meal from the birds, include the stable fly, *Stomoxys calcitrans* (Linnaeus) [Diptera: Muscidae], and various species of mosquitoes [Culicidae], biting midges [Ceratopogonidae], and black flies [Simuliidae] (Arends 1991). The stable fly may breed in the litter and manure in poultry houses but seldom in significant numbers. Most stable flies breed outside the houses in accumulations of rotting vegetative matter and in livestock manure mixed with straw or other bedding material. The mosquitoes develop outside the houses in any standing water. An important mosquito breeding source is the poultry waste lagoons if they are not properly designed and managed; the major species are *Culex quinquefasciatus* Say in warm climates and *C. pipiens* Linnaeus in cool climates (Rutz and Axtell 1978). The biting midges (*Culicoides*) develop outside the houses in very moist soil (especially when contaminated with animal manure) and in nearby lowlying wet areas. The black flies (various species) develop outside the houses in moving water in streams. The invasion of poultry houses by mosquitoes, biting midges, and black flies sometimes is a major problem and a source of disease transmission among poultry operations.

Moths

Infested feed can cause the development of substantial moth populations in litter and manure. Moth infestations in the auger feed delivery systems results in clogging and inadequte feed delivery to the birds; this is the major economic consequence of moth infestations. Control of the moths once a house and the feed delivery system are infested is difficult and requires thorough cleaning of the entire system. The most common species of moths [Lepidoptera: Pyralidae] are the meal moth, *Pyralis farinalis* Linnaeus, mediterranean flour moth, *Anagasta kuehniella* (Zeller), and the Indian meal moth *Plodia interpunctella* (Hubner). All have the same basic biology with the eggs, three larval stages, and pupae in the feed and litter. The late stage larvae produces a webbing material which causes the feed and litter to form clumps.

Cockroaches

Although not common, sometimes tremendous infestations of cockroaches occur in poultry houses, especially caged-layers and broiler breeders. The roaches not only infest the chicken house but invade the egg handling and storage facilities where their large numbers are a nuisance and the odor is unpleasant. The roaches stain the surfaces and leave fecal deposits. Roaches are easily transported from one facility to another in contaminated egg cases. The species of cockroaches [Dictyoptera] likely to occur are the German, *Blattella germanica* (Linnaeus), American, *Periplaneta americanum* (Linnaeus), and Oriental, *Blatta orientalis* (Linnaeus).

Factors affecting pest populations

The size of a pest population in and around poultry houses depends on abiotic and biotic factors. Abiotic factors refers to conditions of the environment. The most important are temperature and the physical/chemical traits of the habitat. Biotic factors refer to the effects of living organisms; this includes natural enemies (predators, parasites, and pathogens), and competition among the species. Three factors in poultry production determine the nature of the abiotic and biotic factors. These are: housing type and management, waste management, and flock management. These factors are, of course, interrelated.

Housing management

The housing type and management are dictated by the type of poultry being produced, economics, and the preferences in a particular region and climate. In all cases, the confined poultry housing means that the environment is more closely regulated than outside. The temperatures are kept within a range, whenever possible, that is most conducive to egg or meat production. Temperature, moisture, and odor (primarily ammonia) are controlled in part by the use of fans and (in open curtain-sided houses) natural airflow. Proper air flow is necessary for bird health and optimal production. Also, proper air flow is needed to assist in drying the manure and litter to reduce fly breeding. Air flow in open-sided houses is facilitated by cutting the weeds and grass around the house; this also helps in rodent control by reducing harborage. Basic to housing type and management is the initial construction of the facility. The houses should be sited on land graded to promote drainage of rainwater away from the house. Poor drainage that allows rainwater to seep into poultry houses creates fly problems and undermines house foundations. Frequent inspection and repair of feed and water equipment in a house is required to reduce the spillage of feed into the manure and litter, and excess moisture due to leaking water systems. This routine maintenance reduces the cost of production and at the same time reduces the populations of flies and beetles developing the manure and litter.

Waste management

Waste management refers to how the manure, litter, and dead birds are handled. In wide span caged-layer houses, manure accumulates under the cages for several months to a year. In high-rise deep pit caged-layer houses, the manure is allowed to accumulate for 2–4 years. Management of this manure to encourage drying depends largely on the air flow, drainage, and elimination of leaking water systems described under housing management. This drying of the manure is necessary to facilitate the easy manure removal and spreading on fields as well as to reduce fly production. In a similar fashion, proper management of manure under the slats in broiler breeder houses is required to promote drying. Manure removal systems in the caged-layer houses that use flushing or scrapers require optimal maintenance of the removal equipment and frequent (daily) use to avoid residual deposits of manure that build up over time. Such accumulations of manure reduce the efficiency of the removal equipment and provide fly breeding habitat. Flushing the manure into a lagoon is a common disposal method that recycles the lagoon water for the flushing process. Proper design and management of the lagoon is required to prevent mosquito breeding. Deep lagoons with steep sides and the margins free of vegetation do not usually support mosquito breeding.

Litter used in parts of breeder houses and in growout houses contains a mixture of some feces, spilled feed, and feathers in the wood shavings (or other dry material initially provided). Excess spilled feed is undesirable economically and because it encourages beetle production. Dry litter is accomplished by the same drying factors described above for manure: proper air flow, drainage, and elimination of water leaks. The frequency of litter removal from growout houses is often dictated by economics but the longer the litter is allowed to remain the greater the build up of the beetle population.

Bird mortality is a normal part of poultry production. Even though mortality may be only 1–3%, with the large number of birds in a house this results in sizable numbers of carcasses requiring disposal. Dead birds should be removed daily. Dead birds left in the house or piled outside the house promote insect development, especially blow flies, and may be a source of disease pathogens. Incineration, composting, and burial are acceptable methods of disposal.

Flock management

Flock management refers to the supervision of the general health of the birds including feed and water consumption. Excessive water consumption may be related to the salt content of the feed, the timing of water availability, and high temperatures. Too much water consumption by the birds, as well as improper nutrition or a disease condition, can result in fluid feces which causes wet manure or litter and encourages fly production.

Pest problems are often an indicator of improper housing, waste, and flock management. Obviously, these management practices affect the abiotic factors in the poultry production system with the main effects on temperature, moisture and the condition of the manure and litter. Less directly, these practices also affect the biotic factors. The populations of natural enemies is influenced greatly by abiotic conditions resulting from the management practices. In particular, the condition of the accumulated manure or litter affects how favorable the habitat is for the survival of predators, parasites and pathogens that regulate populations of the pest species.

Pest control methods

Methods for controlling pests in poultry production may be grouped into three categories: Cultural, biological, and chemical. Cultural methods are basic to any control program. Included are biosecurity, waste management, equipment management, and housing management (primarily control of moisture and airflow).

Cultural control

Biosecurity is a term used in the poultry industry referring to all types of measures to prevent the introduction of pests and disease organisms into a poultry facility. Restricting human traffic in and out of a facility, and disinfecting personnel and equipment that do enter, reduces the chances of introducing certain pests, especially ectoparasites which are able to survive without bird hosts for a few days to several weeks. Transmission of fowl mites, chicken mites, and bedbugs may accidentally occur on workers and equipment. Cockroaches, either as the mobile stages or as ootheca (the egg case) may be transmitted by contaminated equipment, especially poultry egg cases. Contaminated feed delivered from the feed mill may be a route for the introduction of beetles and moths into a house; the feed bins and pipes of the feed delivery system should be periodically cleaned to prevent the build up of pest populations. Restricting access by wild birds reduces the chances of introducing fowl mites, other ectoparasites, and avian diseases. Control of rodent populations removes these incidental hosts for ectoparasites and reservoirs for disease organisms. Domestic cats, which may harbor fleas, should not be allowed in the poultry facilities.

Critical to biosecurity is the thorough cleaning of the house and equipment followed by the proper use of disinfectant and insecticide applications between flocks. The birds used to restock the house must be carefully inspected to assure that they are free of ectoparasites. Restocking caged-layer houses and broiler breeder houses with 18–20 week old birds can result in a serious problem later in the house if even a few of these birds are infested with ectoparasites. Pullet houses should be free of ectoparasites and treated with insecticides if any ectoparasites are detected.

Waste management includes the proper disposal of manure, litter, and dead birds. In housing systems using scraper or flush systems for daily manure removal, the manure may be directed to a lagoon which may be a source of mosquitoes if not properly designed and managed. To minimize mosquito breeding in lagoons the sides must be steep and kept free of vegetation. If the lagoon is too small for the number of birds it will be overloaded and floating masses of manure can be a source of filth flies. In the absence of a lagoon disposal system, the manure which is removed from a house must be either piled and covered to minimize fly development or immediately spread on fields. Manure or litter must be thinly spread on fields and, if possible, turned into the soil. The field spreading should be done during the cooler times of the year in temperate climates to minimize odor and fly problems. Dead birds support the development of blow flies and should be collected daily and removed from the house for disposal by burying, composting, or incineration. In some cases, dead birds are stored and periodically collected for transport to a rendering plant in which case the storage must be in tightly sealed containers away from the poultry house.

Equipment management in relation to pest control refers mainly to the proper maintenance and adjustment of water and feed delivery systems. Leaking water systems results in wet manure or litter which fosters fly development. Poorly adjusted feeding systems results in feed spillage into the manure or litter which not only provides additional nutrients fostering fly and beetle populations, but also increases production costs due to wasted feed. Poultry egg collection systems should be adjusted and maintained so that little or no egg breakage occurs because the high protein egg contamination encourages pest populations, especially blow flies.

Housing management involves grading and construction so that rainwater flows away from the house, as well as the proper adjustment and operation of fans, vents, and side curtains (depending on the particular housing system) to provide adequate air flow and moisture control in the manure and litter. Keeping the manure or litter as dry as possible is essential to control pest populations, especially flies. Keeping the vegetation around the houses cut low is essential for proper airflow and removes harborage for rodents.

Biological control

The use of biological control against pests in poultry production is most advanced in the case of the house fly and closely related filth flies, mainly in production systems (caged-layer and broiler breeder houses) in which the manure is allowed to accumulate for long periods of times (Axtell 1986, 1990, Legner 1995, Wilhoit et al. 1991a). There are two basic approaches to biological control: the encouragement of the populations of natural enemies already present or augmentation through periodic releases (Rutz and Patterson 1990). Parasites attacking the pupal stage of the house fly are sold and released with varying success. Natural populations of parasites usually exist and may be encouraged to increase by assuring that the manure is kept as dry as possible to provide easy access to the pupal stage of the flies. Likewise, keeping the manure as dry as possible encourages natural populations of fly predators.

The most common species of fly parasites [Hymenoptera: Pteromalidae] in poultry houses are *Muscidifurax raptor* Geralt and Sanders, *M. zaraptor* Kogan and Legner, *Spalangia cameroni* Perkins, and *S. nigroaenea* Curtis (Geden 1996, Mann et al. 1990a,b, Rueda and Axtell 1985, Wilhoit et al. 1991c). The most important predators are the histerid beetle, *Carcinops pumilio* (Erichson) [Coleoptera: Histeridae], and the macrochelid mite, *Macrocheles muscaedomesticae* (Scopoli) [Acari: Macrochelidae] (Fletcher et al. 1991, Geden and Axtell 1988a, Geden et al. 1988, Stafford and Bay 1994, Wilhoit et al. 1991a,d, Wills and Mullens 1991). Other manure-inhabiting mite predators are the parasitid mite, *Poecilochirus monospinosus* Wise, Hennessey and Axtell [Acari: Parasitidae], and the uropodid mite, *Fuscuropoda marginata* (Koch) [=*F. vegetans* (De Geer)] [Acari: Uropodidae] (Axtell 1991a, Wise et al. 1988). A variety of other arthropods inhabiting the manure may assist in reducing house fly populations by preying on the fly eggs and early instar larvae (Pfeiffer and Axtell 1980). Consequently, keeping the manure as dry as possible contributes to the development of a heterogeneous manure fauna which results in low house fly populations. Encouragement of biocontrol agents by means of manure management is essential to a fly control program in poultry systems involving manure accumulation (Mullens et al. 1996a,b).

The use of other flies to suppress populations of house flies has been advocated but remains questionable due to inconsistent results and objections to high numbers of flies of any species. The larvae of the dump fly *Hydrotaea* (=*Ophyra) aenescens* preys on house fly larvae and in some circumstances has been effective in suppressing numbers of house fly adults in caged-layer houses (Hogsette and Washington 1995). The larvae of the soldier fly, *Hermetia illucens*, churn the manure making it physically less suitable for house fly oviposition and larval development. Consequently, substantial soldier fly populations may result in low numbers of house flies in a poultry house. However, in most circumstances large numbers of soldier fly larvae are a nuisance and render the manure too fluid for easy removal and disposal.

In addition to parasites and predators, various pathogens affecting flies and beetles occur in poultry production systems. Certain strains of the entomopathogenic fungi *Entomophthora muscae* (Cohn) Fresenius [Zygomycotina: Entomophthorales] and *Beauveria bassiana* (Balsamo) [Deuteromycotina: Hyphomycetes] are widespread and naturally suppress fly populations (Kuramoto and Shimazu 1997, Mullens et al. 1987, Six and Mullens 1996, Watson et al. 1995, Watson and Peterson 1993). These have not been exploited commercially for fly control. Some nematodes kill the house fly experimentally but those strains tested have not survived in poultry manure although some nematode formulations are promising (Renn 1995). The darkling beetle, *Alphitobius diaperinus*, is affected by the fungus, *Beauveria bassiana*, and commercial use may be possible in the future (Steinkraus et al. 1991). The beetle is also naturally suppressed by a parasitic mite, *Acarophenax mahunkai* Steinkraus and Cross [Acari: Acrophenacidae] which destroys beetle eggs (Rueda and Axtell 1997, Steinkraus and Cross 1993). Laboratory experiments have shown the effectiveness of various nematodes for beetle control but a suitable strain for field use has not been identified

(Geden and Axtell 1988b, Geden et al. 1987a). Certain strains of the bacteria, *Bacillus thuriengensis* Berliner, are effective against the house fly and darkling beetle in experimental situations but commercial application has not been developed.

Chemical control

Applications of chemicals for control of arthropod and rodent pests in poultry production systems is common and often necessary in the absence of alternatives. Insecticides commonly used for applications to the structure, manure, litter and birds (depending on label registrations) are: carbaryl, tetrachlorvinphos, dichlorvos, cyfluthrin, fenvalerate, lambda-cyhalothrin, chlorpyrifos, and cyromazine. Methomyl is commonly used in fly baits. Use of disinfectants for disease control is a standard procedure between flocks. Mixing insecticides and disenfectants in one application is often done for convenience and to reduce labor costs. However, this mixing is risky because there is often inactivation of either the insecticide or the disenfectant or both (Geden et al. 1987b).

Fly control is a critical area requiring judicious and selective application of insecticides to avoid interfering with the natural population of predators and parasites attacking the house fly immature stages in caged-layer and broiler breeder houses (Axtell 1986). Protection of those natural enemies from the adverse effects of insecticide applications for fly or other pest control is essential. Chemicals which control house flies are also usually toxic to the natural enemies. Some selectivity is achieved by restricting the insecticide applications to residual treatments of building surfaces where the adult flies rest and by the use of insecticide-baits. Direct insecticide treatment of the manure is not advisable except in very limited areas of exceptionally large fly maggot populations. A feed additive, cyromazine, is an insect growth regulator (IGR) which is selective for fly larvae and effective in fly control with little adverse effect on predacious beetles and mites in the manure; it is used mainly in caged-layer and broiler breeder flocks (Axtell and Edwards 1983). Cyromazine is also used as a spray on manure. House fly control is complicated by the rapid development of insecticide resistance, including some resistance to pyrethroids and cyromazine (Liu and Scott 1995, Pap and Farkas 1994, Popischil et al. 1996). The use of chemicals, such as triflumuron, for autosterilization of house flies has been proposed and demonstrated experimentally (Howard and Wall 1996a,b).

Beetle control relies mainly on insecticide treatment of the litter, and sometimes the underlying soil, in broiler and turkey growout houses. In most cases, beetle populations rebound a few weeks after treatment. The most satisfactory control is achieved by treating between each flock. Likewise, the control of ectoparasites relies on applications of insecticides to the birds and to the housing. Although some chemicals used as feed additives have shown effectiveness for ectoparasite control, none are in commercial use due to insecticide residue problems in the meat and eggs. Fowl mite control requires penetration of the feathers with a relatively high presssure spray which is difficult to achieve, especially in caged-layer houses with the cages stacked close together (Arthur and Axtell 1983a, Fletcher and Axtell 1991). Mites can be controlled with insecticide-impregnated strips hung in the cages or placed in nest boxes but the costs and labor required for installation have limited their use (Axtell 1991b). Chicken mites and bedbugs, which spend most of their time off the host, require thorough spraying of the house and equipment, especially in the cracks and crevices (Fletcher and Axtell 1993).

Special formulations of insecticides with pheromones and attractants improve control. These are limited in applications for poultry production pests. Formulations for house fly baits containing the sex pheromone (Z)-9-tricosene (muscalure) or other attractants are effective for adult fly control (Mitchell et al. 1975, Learmount et al. 1996). Also, muscalure improves the effectiveness of fly-electrocuting black light devices (Rutz et al. 1988). Residual insecticide sprays with sugar added improve control of resting adult house flies. A bait formulation for darkling beetle control is commercially available. There is a need for more research and development on the use of pheromones and attractants in the control of poultry pests.

Poultry IPM components

Integrated pest management is a holistic concept being widely adopted. The concept in general is discussed by Dent (1995) and in relation to livestock and poultry production by Axtell (1981). Poultry integrated pest management is based on applied ecology – understanding the pest biology and behavior in the habitat as described above in this paper. The first step in an IPM program is proper identification of the pests. Given the artificial habitat in poultry production facilities there are often cases of usually minor pests developing into a major problem. Overall, the most common pest problems are house flies, litter beetles, fowl mites, and rodents. Pest diagnosis is facilitated by a computer expert system program (PPES – Poultry Pest Expert System) available for downloading from the Internet (World Wide Web) at http://ipmwww.ncsu.edu/vetent/expert.html.

Monitoring

Pest population monitoring is the basis of poultry IPM. A monitoring program usually is focused on a few pests most likely to be encountered in a particular type of poultry production facility. Ectoparasites are monitored in a flock by inspection of selected birds for the presence of fowl mites and lice or symptoms (skin lesions) of feeding by chicken mites and bedbugs. Fowl mites are most abundant in the vent region of hens. In caged-layer systems, the birds occurring singly (due to death of cage mates) in a cage should be inspected first because they are most likely to have the greatest fowl mite populations (Arthur and Axtell 1983b). Inspection of crack and crevices, roosts, slats, and nest boxes for the presence of chicken mites and bedbugs is required due to those pests feeding only intermittently on the host and spending most of their life cycle in the habitat.

House fly monitoring methods are well developed and involve visual inspection of the manure and litter for fly larvae and sampling of the adult fly activity by spot cards, baited jug traps, and sticky ribbons or sticky cards, and visual observations of flies resting in designated areas (Lysyk and Axtell 1986, Hogsette et al. 1993). The use of spot cards (Axtell 1970), which measure fly activity by the numbers of regurgitation and fecal spots over several days, has been widely accepted as a convenient sampling method. The actual density of house flies has been related to the fly abundance index obtained with spot cards (Lysyk and Axtell 1985).

Monitoring litter beetle populations in the litter of growout houses is by visual inspection and the use of tube traps consisting of a roll of corrugated cardboard inside an open-ended section of plastic pipe placed on the litter for several days (Safrit and Axtell 1984). Both adults and larvae of the beetle accumulate in the cardboard and give an indication of the population level in the litter. Rodents are monitored by inspection for the presence of fresh feces in the house and for openings to burrows in and outside the house. In housing systems with manure accumulations, mouse burrow openings can be observed in the piled manure. The depletion of rodent baits placed in bait stations and in burrow openings is another measure of rodent populations.

All of these monitoring methods should be routinely applied to detect pest problems early enough to apply corrective actions before the problem becomes too difficult to correct in a reasonable time. The monitoring procedures also are useful in measuring the effectiveness of control actions after they are applied.

The meaning of monitoring data depends on the circumstance. Accurate records of the monitoring data allows the producer and integrator to detect any correlations of pest intensity with poor flock performance. Because the integrators have accurate records on flock performance for their large operations, they are able to fine-tune all aspects of production, including pest management, to achieve the highest rate of return. This has been facilitated by the recent widespread use of computers for poultry production records and analysis. Those records are confidential but conversations with integrators often reveal that they have considerable insight into what levels of ectoparasites, litter beetles, rodents, etc. adversely impact their operations. Because those records are not open to the public, there is a lack of detailed economic loss data in the literature. Experiments to determine economic losses from pest infestations are of limited value due to the practical necessity to use relatively small numbers of birds. With the large numbers of birds involved in commercial poultry production even a very small loss per bird (in terms of feed conversion, weight gains, egg production, etc.) becomes a significant cost to the producer and integrator. In general, detection of only a few ectoparasites on a few birds or in the habitat is justification for instigating further control measures to prevent the spread of the parasites throughout a flock. An exception to this approach may be when the flock is old and nearing the time for replacement, in which case additional ectoparasite control measures may not be cost effective. Complete ectoparasite control on pullets is necessary to prevent introduction of the pests into other houses at the time of restocking.

The significance of the numbers of flies detected by monitoring is related to the nearness of human housing and businesses to the poultry facility. Generally, the closer the neighbors the fewer flies which can be tolerated. Lawsuits and actions under public health laws due to fly annoyance can result in significant economic loss and even closing the poultry operation. Low beetle numbers are desired to avoid the cost of repair to damaged buildings, the interference with normal feed consumption and growth of the birds, and the losses due to various avian disease organisms maintained by the beetles. Also, low beetle numbers are desirable to minimize dispersal to other poultry houses and dispersal to human dwellings when used litter is spread on fields. Low rodent numbers, likewise, are an objective to reduce building damage and feed loss, and to eliminate a potential reservoir for disease organisms. Rodents may also move to nearby human dwellings creating a legal and public health problem.

Control measures

Pest control in poultry facilities requires a judicious meshing of the cultural, biological, and chemical methods described previously. Biosecurity is always a primary element for preventing as much as possible the introduction of disease organism and pests into the operation. Optimal flock, housing, and waste management procedures should be continuously practiced to assist in suppressing pest populations and to encourage natural control factors, including moisture control, fly parasites and fly predators. When monitoring indicates unacceptable pest levels, additional actions are required to improve the implementation of the management practices. In addition, chemical applications may be necessary. The timing of insecticide applications must be meshed with the poultry management practices. Very often this restricts applications to between flocks in a house when thorough cleaning and spraying is possible as for beetle, chicken mite, and bedbug control. Chemical applications for fly control by residual spraying, insecticide–bait mixtures and occasional misting are sometimes necessary to bring the adult fly population down to an acceptable level. However, those applications must be made with minimal contamination of the manure to preserve the natural populations of fly parasites and predators (Wills et al. 1990). Only spot treatment of the manure in areas of exceptionally large numbers of fly larvae and not overall treatment with insecticide is recommended. In some cage-layer flocks, the addition of cyromazine to the feed is an integral part of the fly control program and is usually used for several weeks and then stopped for several weeks to lessen the rate of resistance development and the cost. Fly population monitoring in those facilities is important for refining the timing of the use of the feed additive. Rodent control, after infestations are detected, is routinely accomplished by the use of one or more of several rodenticide bait formulations applied to rodent burrows and placed in bait stations.

Laws and regulations

A part of a poultry IPM program is conforming with local laws and regulations relevant to waste disposal, water quality, and public health. This is variable within regions of a nation and among nations. More and more, however, restrictions are being placed on the spreading of manure and litter, on the use of lagoons for manure disposal and on the disposal of dead birds. In some nations, especially western Europe, restrictions are being placed on the type of cages and degree of confinement of poultry. There is a trend to ‘free range’ poultry production in which the birds are not confined in cages and have free access to outdoor areas adjacent to the houses; this complicates the pest problems with greater chances for ectoparasite infestations and disease transmission. Public health laws in most places provide restrictions on any activity which produces insect and rodent pests which may affect human welfare.

Implementation

Instituting and operating poultry IPM is a joint responsibility of the integrator and contract producers. Service persons employed by the integrator regularly visit each producer and oversee flock health and production. These workers are most often trained in poultry science and have limited or no background in entomology and pest management. Additional training is usually needed for those persons and the producer to initiate and maintain a poultry IPM program. The IPM program is one part of the total poultry production endeavor and is most successful when implemented as an interrelated component of the system. The system approach takes into account all aspects of animal nutrition and production, pest biology and control options, results of pest population monitoring, and the comparative costs versus benefits of pest management.

Summary and prospects

Poultry IPM is possible with the techniques and knowledge currently available. Although the interactions are complex, a judicious combination of cultural, biological and chemical control methods meshed with optimal flock, waste, and housing management practices in a systems approach is feasible. In the case of house fly population management a computer simulation program incorporating the dynamics of fly predators and parasites as well as various manure removal and chemical control measures has been developed. This program (FMS – Fly Management Simulator) is available for downloading on the Internet (World Wide Web) at http://ipmwww.ncsu.edu/vetent/expert.html. This simulation model and its components are documented in a technical manual which contains an extensive list of references (Wilhoit et al. 1991a). Computer simulation models for other pests need to be developed in the future to deal with the complexities of pest management in poultry production systems. It is difficult to analyze all of the interactions without the assistance of such models.

In the future, new techniques and knowledge will facilitate improvements in poultry IPM. New classes of insecticides and insect growth regulators (IGRs), as well as improved formulations, such as microencapsulation, are being developed and some will be applicable to the poultry pest problems. Likewise, new species and strains of biological control agents will be found. Improved baits, attractants, and traps will provide better tools. These developments will allow more effective integration of biological and chemical methods in poultry IPM.

Actual implementation of poultry IPM programs has been limited and not well documented. In some regions of the United States programs have been promoted by University personnel (Arends and Robertson 1986, Loomis 1986). Shortage of service persons in the poultry industry with training in IPM has been a major limitation. In the future that needs to be changed with special training courses and improved knowledge transfer through computer aids targeted to the problems of the poultry industry.

The prospects for wider use of IPM in the poultry industry are bright. The highly integrated nature of the industry means that a structure exists for knowledge transfer through the companies and their representatives to large numbers of contract producers. This organized production system is ideal for disseminating IPM information more rapidly and effectively than in the more diverse crop production area which is not often under the direction of large companies. Because the poultry industry is integrated in all phases (feed mill, hatchery, production, processing, and final product distribution), future IPM programs must be expanded to include all phases of the system and not simply the bird production aspect. This means providing IPM knowledge for feed mills, hatcheries, processing plants, and the warehouses and distribution system. With the extensive data bases accumulated by the integrators, the industry is becoming increasingly aware of the significant cost : benefit ratios associated with improved pest management. An overall fear and concern for avian and human diseases being maintained or vectored by pests will continue to cause the industry to pay more attention to pest management. The IPM approach offers a means to minimize the use of insecticides which corresponds with a desire in the poultry industry to avoid any presence of foreign chemicals in their products. Also, the IPM approach offers the industry a way to reduce the likelihood of financial losses due to regulatory and legal actions related to nuisance pests. Most important is the fact that the IPM approach is needed to achieve satisfactory levels of pest control.

The specifics of IPM must continually evolve to adapt to new housing and production practices and the introduction of new genetic breeds of birds. The primary breeders (companies who select optimal genetic strains of birds and provide the breeding stock to production companies) are operating worldwide. The new bird strains selected for optimal feed conversion and production efficiency may simultaneously have different susceptibilities to ectoparasites and diseases. Although theoretically ectoparasites might be controlled by vaccines and breed selection, these approaches are not practical and the key to effective pest control will remain the IPM approach based on applied ecology.

The worldwide expansion of poultry production will continue. This will increase adoption of IPM programs. The expansion of the poultry industry in many nations will necessitate the wider dissemination of IPM knowledge and the World Wide Web will be one important mechanism. The pattern of an integrated poultry production industry with large companies and contract producers is being adopted worldwide as the most efficient and practical business plan. Many companies in developed nations are becoming global as they enter joint ventures with poultry production companies in the less developed nations. The methods of poultry housing and production are similar worldwide. These factors will facilitate future research, development, and implementation of poultry IPM. The practical question is: Who will provide the funding and personnel? In the absence of more University and government research and education efforts, in the future the poultry industry will have to fund advances in poultry IPM.

Acknowledgements

Numerous entomologists, poultry scientists, veterinarians, and poultry producers have contributed over many years to the author's understanding of poultry pest management problems. The research and intellectual contributions of many graduate students and postdoctoral research associates has been critical. The practical insights and suggestions provided by M. Stringham (Extension Entomologist) and T. Carter (Extension Poultry Scientist) at North Carolina State University are gratefully acknowledged. However, the author accepts full responsibility for the content and views expressed in this publication.

References

Adams, R.G. (1984) *Ophyra* species as predators in animal houses, with a key to species occurring in Europe (Diptera: Muscidae). *Entomologist's Gazette* **35**, 243–6.

Arends, J.J. (1991) External parasites and poultry pests. In B.W. Calnek, H.J. Barnes, C.W. Beard, W.M. Reid and H.W. Yoder, Jr. (eds) *Diseases of Poultry, Ninth edn* pp. 702–30. Ames: Iowa State University Press.

Arends, J.J. and S.H. Robertson (1986) Integrated pest management for poultry production: implementation through integrated poultry companies. *Poultry Science* **65**, 675–82.

Arthur, F.H. and Axtell, R.C. (1983a) Susceptibility of northern fowl mites in North Carolina to five acaricides. *Poultry Science* **62**, 428–32.

Arthur, F.H. and Axtell, R.C. (1983b) Northern fowl mite population development on laying hens caged at three colony sizes. *Poultry Science* **62**, 424–7.

Axtell, R.C. (1970) Integrated fly control program for caged-layer poultry houses. *Journal of Economic Entomology* **63**, 400–5.

Axtell, R.C. (1981) Livestock integrated pest management (IPM): principles and prospects. In F.W. Knapp (ed) *Systems Approach to Animal Health and Production* pp. 31–40. Lexington: University of Kentucky.

Axtell, R.C. (1986) Fly management in poultry production: cultural, biological, and chemical. *Poultry Science* **65**, 657–67.

Axtell, R.C. (1990) Potential of biocontrol for livestock and poultry pests. In D.A. Rutz and R.S. Patterson (eds) *Biocontrol of Arthropods Affecting Livestock and Poultry* pp. 293–304. Boulder: Westview Press.

Axtell, R.C. (1991a) Role of mesostigmatid mites in integrated fly control. In F. Dusbabek and V. Bukva (eds) *Modern Acarology, Vol 2* pp. 639–46. Prague: Academia.

Axtell, R.C. (1991b) Control of northern fowl mites on poultry. In F. Dusbabek and V. Bukva (eds.) *Modern Acarology, Vol 2* pp. 709–12. Prague: Academia.

Axtell, R.C. and Edwards, T.D. (1983) Efficacy and non-target effects of Larvadex® as a feed additive for controlling house flies in caged-layer poultry manure. *Poultry Science* **62**, 2371–7.

Axtell. R.C. and Arends, J.J. (1990) Ecology and management of arthropod pests of poultry. *Annual Review of Entomology* **35**, 101–26.

Barnard, D.R. and Geden, C.J. (1993) Influence of larval density and temperature in poultry manure on development of the house fly (Diptera: Muscidae). *Environmental Entomology* **22**, 971–7.

Barnard, D.R., Harms, R.H. and Sloan, D.R. (1995) Influence of nitrogen, phosphorus, and calcium in poultry manure on survival, growth, and reproduction in the house fly (Diptera: Muscidae). *Environmental Entomology* **24**, 1297–301.

Beugnet, F., Chauve, C., Gauthey, M. and Beert, L. (1997) Resistance of the red poultry mite to pyrethroids in France. *Veterinary Record* **140**, 577–9.

Calnek, B.W., Barnes, H.J., Beard, C.W., Reid, W.M. and Yoder, Jr., H.W. (eds) (1991) *Diseases of Poultry, Ninth Edition*. Ames: Iowa State University Press.

Cotton, J.J. (1970) The life history of the hen flea, *Ceratophyllus gallinae* (Siphonaptera: Ceratophyllidae). *Entomologist* **105**, 45–8.

Dent, D.R. (1995) *Integrated Pest Management*. London: Chapman & Hall.

Despins, J.L. and Axtell, R.C. (1994) Feeding behavior and growth of turkey poults fed larvae of the darking beetle, *Alphitobius diaperinus*. *Poultry Science* **73**, 1526–33.

Despins, J.L. and Axtell, R.C. (1995) Feeding behavior and growth of broiler chicks fed larvae of the darkling beetle, *Alphitobius diaperinus*. *Poultry Science* **74**, 331–6.

Despins, J.L., Axtell, R.C., Rives, D.V., Guy, J.S. and Ficken, M.D. (1994) Transmission of enteric pathogens of turkeys by darkling beetle larva (*Alphitobius diaperinus*). *Journal of Applied Poultry Research* **3**, 61–5.

Dryden, W.W. and Rust, M.K. (1994) The cat flea: biology, ecology and control. *Veterinary Parasitology* **52**, 1–19.

Fatchurochim, S., Geden, C.J. and Axtell, R.C. (1989) Filth fly (Diptera) oviposition and larval development in poultry manure of various moisture levels. *Journal of Entomological Science* **24**, 224–31.

Fletcher, M.G. and Axtell, R.C. (1991) Susceptibilities of northern fowl mite, *Ornithonyssus sylviarum* (Acarina: Macronyssidae) and chicken mite, *Dermanyssus gallinae* (Acarina: Dermanyssidae), to selected acaricides. *Experimental and Applied Acarology* **13**, 137–42.

Fletcher, M.G. and Axtell, R.C. (1993) Susceptibility of the bedbug, *Cimex lectularius* L., to selected insecticides and various treated surfaces. *Medical and Veterinary Entomology* **7**, 69–72.

Fletcher, M.G., Axtell, R.C., Stinner, R.E. and Wilhoit, L.R. (1991) Temperature-dependent development of immature *Carcinops pumilio* (Coleoptera: Histeridae), a predator of *Musca domestica* (Diptera: Muscidae). *Journal of Entomological Science* **26**, 99–108.

Geden, C.J. (1996) Modeling host attacks and progeny production of *Spalangia gemina*, *Spalangia cameroni*, and *Muscidfurax raptor* (Hymenoptera: Pteromalidae) at constant and variable temperatures. *Biological Control* **7**, 172–8.

Geden, C.J. and Axtell, R.C. (1987) Factors affecting climbing and tunneling behavior of the lesser mealworm, *Alphitobius diaperinus* (Coleoptera: Tenebrionidae). *Journal of Economic Entomology* **80**, 1197–204.

Geden, C.J. and Axtell, R.C. (1988a) Predation by *Carcinops pumilio* (Coleoptera: Histeridae) and *Macrocheles muscaedomesticae* (Acarina: Macrochelidae) on the house fly (Diptera: Muscidae): functional response, effects of temperature, and availability of alternative prey. *Environmental Entomology* **17**, 739–44.

Geden, C.J. and Axtell, R.C. (1988b) Effect of temperature on nematode (*Steinernema feltiae* [Nematoda: Steinernematidae]) treatment of soil for control of lesser mealworm (Coleoptera: Tenebrionidae) in turkey houses. *Journal of Economic Entomology* **81**, 800–3.

Geden, C.J., Stinner, R.E. and Axtell, R.C. (1988) Predation by predators of the house fly in poultry manure: effects of predator density, feeding history, interspecific interference, and field conditions. *Environmental Entomology* **17**, 320–9.

Geden, C.J., Arends, J.J. and Axtell, R.C. (1987a) Field trials of *Steinernema feltiae* (Nematoda: Steinernematidae) for control of *Alphitobius diaperinus* (Coleoptera: Tenebrionidae) in commercial broiler and turkey houses. *Journal of Economic Entomology* **80**, 136–41.

Geden, C.J, Arends, J.J. and Axtell, R.C. (1987b) Efficacies of mixtures of disinfectants and insecticides. *Poultry Science* **66**, 659–65.

Harrington, L.C. and Axtell, R.C. (1994) Comparisons of sampling methods and seasonal abundance of *Drosophila repleta* in caged-layer poultry houses. *Medical and Veterinary Entomology* **8**, 331–9.

Hoglund, J., Nordenfors, H. and Uggla, A. (1995) Prevalence of the poultry red mite, *Dermanyssus gallinae*, in different types of production systems for egg layers in Sweden. *Poultry Science* **74**, 1793–8.

Hogsette, J.A. and Washington, F. (1995) Quantitative mass production of *Hydrotaea aenescens* (Diptera: Muscidae). *Journal of Economic Entomology* **88**, 1238–42.

Hogsette, J.A., Butler, J.F., Miller, W.V. and Hall, R.D. (1991) Annotated bibliography of the northern fowl mite, *Ornithonyssus sylviarum* (Canestrini & Fanzago) (Acari: Macronyssidae). *Entomological Society of America, Miscellaneous Publication* **76**, 1–62.

Hogsette, J.A., Jacobs, R.D. and Miller, R.W. (1993) The sticky card: device for studying the distribution of adult house fly (Diptera: Muscidae). *Journal of Economic Entomology* **86**, 450–4.

Howard, J. and Wall, R. (1996a) Control of the house fly, *Musca domestica*, in poultry units: current techniques and future prospects. *Agricultural Zoology Reviews* **7**, 247–65.

Howard, J. and Wall, R. (1996b) Autosterilization of the house fly, *Musca domestica*, using the chitin synthesis inhibitor triflumuron on sugar-baited targets. *Medical and Veterinary Entomology* **10**, 97–100.

Jeffries, M.G. (1980) The occurrence of *Dermestes* species (Coleopter: Dermestidae) in ‘deep pit’ poultry houses in Britain. *Entomologists’s Gazette* **30**, 207–12.

Jones, F.T., Axtell, R.C., Rives, D.V., Scheideler, S.S., Traver, Jr., F.R., Walker, R.L. and Wineland, M.J. (1991a) A survey of *Salmonella* contamination in modern broiler production. *Journal of Food Protection* **54**, 502–7.

Jones, F.T., Axtell, R.C., Rives, D.V., Scheideler, S.S., Traver, Jr., F.R., Walker, R.L. and Wineland, M.J. (1991b) A survey of *Campylobacter jejuni* contamination in modern broiler production and processing systems. *Journal of Food Protection* **54**, 259–62.

Kells, S.A. and Surgeoner, G.A. (1996) Dispersion of northern fowl mites, *Ornithonyssus sylviarum*, between poultry facilities via infested eggs from layer and breeder flocks. *Journal of Agricultural Entomology* **13**, 265–74

Kells, S.A. and Surgeoner, G.A. (1997) Sources of northern fowl mite (*Ornithonyssus sylviarum*) infestation in Ontario egg production facilities. *Journal of Applied Poultry Research* **6**, 221–8.

Kohls, G.M., Hoogstraal, H., Clifford, C.M. and Kaiser, M.N. (1970) The subgenus *Persicargas* (Ixodoidea, Argasidae, *Argas*). 9. Redescription and new world records of *Argas* (*P.*) *persicus* (Oken), and resurrection, redescription, and records of *A.* (*P.*) *radiatus* Raillet, *A* (*P.*) *sanchezi* Duges, and *A.* (*P.*) *miniatus* Koch, new world ticks misidentified as *A.* (*P.*) *persicus*. *Annals of the Entomological Society of America* **63**, 590–606.

Kuramoto, H. and Shimazu, M. (1997) Control of house fly populations by *Entomophthora muscae* (Zygomycotina: Entomophthorales) in a poultry house. *Applied Entomology and Zoology* **32**, 325–31.

Learmount, J., Chapman, P.A., Morris, A.W. and Pinniger, D.B. (1996) Response of strains of housefly, *Musca domestica* (Diptera: Muscidae) to commercial bait formulations in the laboratory. *Bulletin of Entomological Research* **86**, 541–6.

Legner, E.F. (1995) Biological control of Diptera of medical and veterinary importance. *Journal of Vector Ecology* **20**, 59–120.

Lemke, L.A. and Kissam, J.B. (1986) The status of northern fowl mite research: How far have we come? *Journal of Agricultural Entomology* **3**, 255–64.

Liu, N. and Scott, J.G. (1995) Genetics of resistance to pyrethroid insecticides in the house fly, *Musca domestica*. *Pesticide Biochemistry and Physiology* **52**, 116–24.

Loomis, E.C. (1986) Practical integrated management systems operated on a county-based system. *Poultry Science* **65**, 683–6.

Lysyk, T.J. and Axtell, R.C. (1985) Comparison of baited jug-trap and spot cards for sampling house fly, *Musca domestica* (Diptera: Muscidae), populations in poultry houses. *Environmental Entomology* **14**, 815–19.

Lysyk, T.J. and Axtell. R.C. (1986) Field evaluation of three methods for monitoring populations of house flies (*Musca domestica*) (Diptera: Muscidae) and other filth flies in three types of poultry housing systems. *Journal of Economic Entomology* **79**, 144–51.

Mann, J.A., Stinner, R.E. and Axtell, R.C. (1990a) Parasitism of house fly (*Musca domestica*) pupae by four species of Pteromalidae (Hymenoptera): Effects of host-parasitoid densities and host distribution. *Medical and Veterinary Entomology* **4**, 235–43.

Mann, J.A., Axtell, R.C. and Stinner, R.E. (1990b) Temperature-dependent development and parasitism rates of four species of Pteromalidae (Hymenoptera) parasitoids of house fly (*Musca domestica*) pupae. *Medical and Veterinary Entomology* **4**, 245–53.

Mauer, V. and Baumgartner, J. (1992) Temperature influence on life table statistics of the chicken mite *Dermanyssus gallinae*

(Acari, Dermanyssidae). *Experimental and Applied Acarology* **15**, 27–40.

McAllister, J.C., Steelman, C.D. and Skeeles, J.K. (1994) Reservoir competence of the lesser mealworm (Coleoptera: Tenebrionidae) for *Salmonella typhimurium* (Eubacteriales: Enterobacteriaceae). *Journal of Medical Entomology* **31**, 369–72.

McAllister, J.C., Steelman, C.D., Newberry, L.A. and Skeeles, J.K. (1995) Isolation of infectious bursal disease virus from the lesser mealworm, *Alphitobius diaperinus* (Panzer). *Poultry Science* **74**, 45–9.

McAllister, J.C., Steelman, C.D., Skeeles, J.K., Newberry, L.A. and Gbur, E.E. (1996) Reservoir competence of *Alphitobius diaperinus* (Coleoptera: Tenebrionidae) for *Escherichia coli* (Eubacteriales: Enterobacteriaceae). *Journal of Medical Entomology* **33**, 983–7.

Mitchell, R.R., Tingle, F.C. and Carlson, D.A. (1975) Effect of muscalure on house fly traps of different color and location in poultry houses. *Journal of the Georgia Entomological Society* **10**, 168–74.

Mullens, B.A., Hinkle, N.C. and Szijj, E.E. (1996a) Role of the poultry manure pad in manure drying and its potential relationship to filth fly control. *Journal of Agricultural Entomology* **13**, 331–7.

Mullens, B.A., Hinkle, N.C. and Szijj, C.E. (1996b) Impact of alternating manure removal schedules on pest flies (Diptera: Muscidae) and associated predators (Coleoptera: Histeridae, Staphylinidae; Acarina: Macrochelidae) in caged-layer poultry manure in southern California. *Journal of Economic Entomology* **89**, 1406–17.

Mullens, B.A., Rodriquez, J.L. and Meyer, J.A. (1987) An epizootiological study of *Entomophthora muscae* in muscoid fly populations on southern California poultry facilities, with an emphasis on *Musca domestica*. *Hilgardia* **55**, 1–41.

Nakamae, H., Fujisaki, K., Kishi, S., Yashiro, M., Oshiro, S. and Furuta, K. (1997a) The new parasite ecology of chicken mites *Dermanyssus gallinae* parasitizing and propagating on chickens even in the daytime. *Japanese Poultry Science* **34**, 110–16.

Nakamae, H., Kishi, S., Fujisaki, K, Oshiro, S. and Furuta, K. (1997b) Incidence of the parasitism of chicken mite *Dermanyssus gallinae* parasitizing and propogating on chicken even in the daytime and their life cycle. *Japanese Poultry Science* **34**, 240–7.

North, M.O. and Bell, D.D. (1990) *Commercial Chicken Production Manual, 4th edn.* New York: Chapman & Hall.

Pap, R. and Farkas, R. (1994) Monitoring of resistance of insecticides in house fly (*Musca domestica*) populations in Hungary. *Pesticide Science* **40**, 245–58.

Parkhurst, C.R. and Mountney, G.J. (1988) *Poultry Meat and Egg Production.* New York: Van Nostrand Reinhold.

Pfeiffer, D.G. and Axtell, R.C. (1980) Coleoptera of poultry manure in caged-layer houses in North Carolina. *Environmental Entomology* **9**, 21–8.

Popischil, R, Szomm, K., Londershausen, M., Schroeder, I, Turber, A. and Fuchs, R. (1996) Multiple resistance in the larger house fly *Musca domestica* in Germany. *Pesticide Science* **48**, 333–41.

Price, M.A. and Graham, O.H. (1997) Chewing and sucking lice as parasites of mammals and birds. *United States Department of Agriculture, Agriculture Research Service Technical Bulletin* **1849**, 1–309.

Renn, N. (1995) Mortality of immature houseflies (*Musca domestica* L.) In artificial diet and chicken manure after exposure to encapsulated entomopathogenic nematodes (Rhabditida: Steinernematidae, Heterorhabditidae). *Biocontrol Science and Technology* **5**, 349–59.

Rueda, L.M. and Axtell, R.C. (1985) Guide to common species of pupal parasites (Hymenoptera: Pteromalidae) of the house fly and other muscoid flies associated with poultry and livestock manure. *North Carolina Agricultural Research Service Bulletin* **278**, 1–88.

Rueda, L.M. and Axtell, R.C. (1996) Temperature-dependent development and survival of the lesser mealworm, *Alphitobius diaperinus* (Coleoptera: Tenebrionidae). *Medical and Veterinary Entomology* **10**, 80–6.

Rueda, L.M. and Axtell, R.C. (1997) Arthropods in litter of poultry (broiler chicken and turkey) houses. *Journal of Agricultural Entomology* **14**, 81–91.

Rutz, D.A. and Axtell, R.C. (1978) Factors affecting production of the mosquito, *Culex quinquefasciatus* (=*fatigans*) from anaerobic animal waste lagoons. *North Carolina Agricultural Experiment Station Technical Bulletin* **256**, 1–32.

Rutz, D.A. and Patterson, R.S. (eds) (1990) *Biocontrol of Arthropods Affecting Livestock and Poultry*. Boulder: Westview Press.

Rutz, D.A., Scoles, G.A. and Howser, G.G. (1988) Evaluations of fly-electrocuting black light devices in caged-layer poultry facilities. *Poultry Science* **67**, 871–7.

Safrit, R.D. and Axtell, R.C. (1984) Evaluations of sampling methods for darkling beetles (*Alphitobius diaperinus*) in the litter of turkey and broiler houses. *Poultry Science* **63**, 2368–75.

Shepard, D.C., Newton, G.L., Thompson, S.A. and Savage, S. (1994) A value added manure management system using the black soldier fly. *Bioresource Technology* **50**, 275–9.

Six, D.L. and Mullens, B.A. (1996) Seasonal prevalence of *Entomophthora muscae* and introduction of *Entomophthora schizophorae* (Zygomycotina: Entomophthorales) in *Musca domestica* (Diptera: Muscidae) populations on California dairies. *Biological Control* **6**, 315–23.

Skidmore, P. (1985) *The Biology of the Muscidae of the World*. Dordrecht, Netherlands: W. Junk Publishers.

Stafford, K.C., III, and Bay, D.E. (1994) Dispersion statistics and sample size estimates for house fly (Diptera: Muscidae) larvae and *Macrocheles muscaedomesticae* (Acari: Macrochelidae) in poultry manure. *Journal of Medical Entomology* **31**, 732–7.

Steinkraus, D.C. and Cross, E.A. (1993) Description and life history of *Acarophenax mahunkai*, n. sp. (Acari, Tarsonemina: Acarophenacidae), an egg parasite of the lesser mealworm (Coleoptera: Tenebrionidae). *Annals of the Entomological Society of America* **86**, 239–49.

Steinkraus, D.C., Geden, C.J. and Rutz, D.A. (1991) Susceptibility of lesser mealworm (Coleoptera: Tenebrionidae) to *Beauveria bassiana* (Moniliales: Moniliaceae): Effects of host stage, substrate, formulation, and host passage. *Journal of Medical Entomology* **28**, 314–21.

Stevens, J. and Wall, R. (1996) Species, sub-species and hybrid populations of the blowflies *Lucilia cuprina* and *Lucilia sericata* (Diptera: Calliphoridae). *Proceedings of the Royal Society of London B* **263**, 1335–41.

Stevens, J. and Wall, R. (1997) The evolution of ectoparasitism in the genus *Lucilia* (Diptera: Calliphoridae). *International Journal for Parasitology* **27**, 51–9.

Usinger, R.L. (1966) Monograph of Cimicidae. *Entomological Society of America, Thomas Say Foundation* **7**, 1–585.

U.S. Government (1998) United States Department of Agriculture, Foreign Agricultural Service, Internet address, http://www.fas.usda/dlp.

Wallace, M.M.H., Winks, R.G. and Voestermans, J. (1985) The use of the beetle, *Alphitobius diaperinus* (Panzer) (Coleoptera: Tenebrionidae) for the biological control of poultry dung in high-rise layer houses. *Journal of the Australian Institue of Agricultural Science* **51**, 214–19.

Watson, D.W. and Peterson, J.J. (1993) Seasonal activity of *Entomophthora muscae* (Zygomycetes: Entomophthorales) in *Musca domestica* L. (Diptera: Muscidae) with reference to temperature and humidity. *Biological Control* **3**, 182–90.

Watson, D.W., Geden, C.J., Long, S.J. and Rutz, D.S. (1995) Efficacy of *Beauveria bassiana* for controlling the house fly and stable fly (Diptera: Muscidae). *Biological Control* **5**, 405–11.

Weaver, J.E. (1996) The lesser mealworm, *Alphitobius diaperinus*: field trials for control in a broiler house with insect growth regulators and pyrethroids. *Journal of Agricultural Entomology* **13**, 93–7.

Wilhoit, L.R., Stinner, R.E. and Axtell, R.C. (1991a) Computer simulation model of house fly management in confined-animal production systems. *North Carolina Agricultural Research Service Technical Bulletin* **296**, 1–81.

Wilhoit, L.R., Axtell, R.C. and Stinner, R.E. (1991b) Estimating manure temperatures from air temperatures and results of its use in models of filth fly (Diptera: Muscidae) development. *Environmental Entomology* **20**, 635–43.

Wilhoit, L.R., Stinner, R.E., Axtell, R.C., Bacheler, J.E. and Mann, J.A. (1991c) PARMOD: A model for *Muscidfurax* spp. and *Spalangia* spp. (Hymenoptera: Pteromalidae), parasites of house fly pupae (Diptera: Muscidae). *Environmental Entomology* **20**, 1418–26.

Wilhoit, L.R., Stinner, R.E. and Axtell, R.C. (1991d) CARMOD: A simulation model for *Carcinops pumilio* (Coleoptera: Histeridae) population dynamics and predation on immature stages of house flies (Diptera: Muscidae). *Environmental Entomology* **20**, 1079–88.

Williams, R.E., Hall, R.D., Broce, A.B. and Scholl, P.J. (eds) (1985) *Livestock Entomology*. New York: Wiley.

Wills, L.E. and Mullens, B.A. (1991) Vertical distribution of dipterous larvae and predatory arthropods in accumulated caged layer poultry manure in southern California. *Journal of Agricultural Entomology* **8**, 59–66.

Wills, L.E., Mullens, B.A. and Mandeville, J.D. (1990) Effects of pesticides on filth fly predators (Coleoptera, Histeridae, Staphylinidae, acarina, Macrochelidae, Uropodidae) in caged layer poultry manure. *Journal of Economic Entomology* **83**, 451–7.

Wise, G.U., Hennessey, M.K. and Axtell, R.C. (1988) A new species of manure-inhabiting mite in the genus *Poecilochirus* (Acari: Mesostigmata: Parasitidae) predacious on house fly eggs and larvae. *Annals of the Entomological Society of America* **81**, 209–24.