Chapter 10

WESTERN RESEARCH ON INSECTS AS FOOD AND ANIMAL FEEDSTUFFS

Introduction

It is well-known that insects are an attractive and important natural source of food for many kinds of vertebrate animals, including birds, lizards, snakes, amphibians (toads, frogs, salamanders), fish, Insectivora and other mammals (McHargue 1917; Frost 1942, pp. 62-63; Brues 1946, pp. 399-407, 418; and many others). McHargue cites a U.S. Biological Survey investigation of the stomach contents of 14 species of wild birds revealing that approximately 50% of the annual food consumption consisted of insects. McHargue notes that since insects are available for only about half the year, the wild bird diet consists almost entirely of insects during the seasons when they are present. McHargue states (p. 634): "The avidity with which domestic fowls, when allowed to range, seek insect food is familiar to all, and it is a well-known fact that poultry thrive best when they have access to this kind of food."

Thus, while looked upon in the West with disfavor as food for humans, insects have attracted occasional research attention as feeds for domesticated animals, particularly poultry, swine, freshwater fish, and certain zoo, laboratory and household animals. The vast majority of studies in the West have dealt with the nutritional value of muscoid Diptera larvae/pupae used to recycle nutrients from poultry manure or other organic wastes as a high-protein source for broiler production.

Redford and Dorea (**1984**) determined the water, ash, total nitrogen and fat content for the worker and soldier castes of nine species of Brazilian termites, and then compared these values with those from other species of termites, ants and 22 other species of terrestrial invertebrates. The tabular data include some species used as human food in various regions of the world. **Studier and Sevick** (**1992**) reported the live and dry mass, water content, nitrogen, sodium, potassium, magnesium, calcium and total iron concentrations for representatives (mostly adults) of 16 orders of insects (360 species) occurring in south-central Michigan. The tabular data include families and a few genera and species that are used somewhere as human food. The authors report that, compared to published nutritional requirements (when meeting caloric requirements) for growth and reproduction in birds and mammals, insects are excellent sources of nitrogen, potassium and magnesium, highly variable sources of sodium and iron, and, rarely, adequate calcium sources. The book by **Slansky and Rodriguez** (**1987**) is a valuable source of information on the nutritional ecology of many insect groups that are important as human food.

Whole dried insects are about 10% chitin, a carbohydrate polymer found in invertebrate exoskeletons, protozoa, fungi and algae. The chitin presents problems of digestibility and assimilability in monogastric animals, but it, and its derivitives, particularly chitosan, possess properties that are of increasing interest in medicine, industry and agriculture. **Goodman** (**1989**) listed some of its capabilities: significantly reducing serum cholesterol, acting as a hemostatic agent, enhancing burn and wound healing, acting as an anticoagulant, protecting against certain pathogens in the blood and skin, serving as a non-allergenic drug carrier, providing a high tensile-strength biodegradable plastic for numerous consumer goods, enhancing pollutant removal from waste-water effluent, improving washability and antistatic nature of textiles, inhibiting growth of pathogenic soil fungi and nematodes, and boosting wheat, barley, oat, and pea yields as much as 20%. Investigators are calling chitin, with its abundance, toughness and biodegradable properties, the polymer of the future, according to Goodman. While insects and fungi have the highest ratio of chitin to body mass and global bioproduction is enormous, the primary source to date has been waste products generated by the shellfish industry. From the foregoing account by Goodman, it seems apparent that if protein concentrates from insects become acceptable and produced on a large scale, the chitin byproduct could be of significant value.

Ritter (**1990**) discussed cholesterol in insects. Like other animals, most insects are approximately 0.1% sterol (i.e., 1 mg sterol/g tissue), but insects are unable to synthesize sterols *de novo* and must obtain them exogenously from the diet or from symbionts. Ritter describes the metabolic conversion, or lack of conversion, of various sterols to cholesterol. Some insects, including edible species such as the honey bee, *Apis mellifera*, and the leaf-cutter ant, *Atta cephalotes isthmicola*, contain no cholesterol. Through diet alterations in which the Δ5-sterols are replaced by other sterols, some other species, which are edible could be produced which contain little, if any, cholesterol. Ritter's research has demonstrated this with the corn earworm, *Heliothis zea*, and it might be done, for example, with the cricket, *Acheta domesticus*, by feeding a diet rich in alfalfa sterols (i.e., Δ7-sterols).

DeFoliart (**1991**) reviewed the available data on insect fatty acids and reports that the proportions of saturated/unsaturated fatty acids are less than 40% saturated in most edible insects, grouping them with poultry and fish. Another notable feature of insect fatty acids is the very high ratio of the polyunsaturates, linoleic and linolenic acids, higher in general than found in poultry and fish.

Coleoptera

McHargue (**1917**) conducted proximate and amino acid analyses on two species of insects, one of which was the June bug, *Lachnosterna* sp. (Family Scarabaeidae) (*Phyllophaga* = *Lachnosterna*). It is stated that analysis showed "such a large percentage of protein present in the dry state," that further studies were conducted, but McHargue doesn't give the percentage found. Data are presented on the amino acid content in comparison to beef roast and turkey white meat. *Lachnosterna* was equivalent to the meats in lysine (8.02% of analyzed nitrogen), slightly lower in arginine (11.53%) and cystine (0.35%) and had only about 50% as much histidine content (6.57%).

Davis (**1918**) noted that the grubs and beetles of *Lachnosterna* are eagerly preyed upon by numerous species of birds and mammals, particularly by crows and blackbirds. Crows often follow the plough, eagerly picking all exposed grubs. Davis cites the U.S. Biological Survey having found these insects in the stomachs of 78 species of birds and two species of toads. Among native mammals, the skunk is probably the most valuable in eating qrubs.

Farm fowls, especially turkeys but others also are fond of both grubs and adults, and the domestic hog "is the most efficient of all grub destroyers where it can be utilized" (Davis, pp. 12-13). According to Davis, the practice of "hogging off" corn, thus saving the expense of harvesting and marketing, is a good preventive control for white grubs as well as cutworms, wireworms and other soil-infesting insects. Advantages include not only (l) control of these insects, but (2) utilization of their food value, and (3) manuring of the land.

Davis cites an example of control in which l00 pigs and 8 sows were turned into a heavily infested l0-acre cornfield in Illinois and destroyed 99% of the grubs within 27 days. Assuming 34.6 grubs per hill (the number at the beginning of the experiment) and the number of hills per acre at 3,556, the pigs destroyed approximately l,217,083 grubs, or 11,278 grubs (24 lbs) per animal. The pigs suffered no ill effects.

Turkeys search diligently for grubs, and Davis states that he has seen infested timothy and sod fields thoroughly scratched up by these birds. Chickens don't search unplowed fields but if allowed the run of the field during ploughing or cultivation they eagerly pick up every grub and beetle exposed. Davis cites an instance in Iowa where a flock of about 150 chickens, encouraged to follow the plough, harrow, and cultivator, practically eliminated the grubs in a badly infested 15-acre field. Davis notes that portable poultry houses have been used in Europe to allow foraging for the European May-beetle grubs.

According to Davis, there are no authenticated reports of harmful dietary effects on either hogs or poultry from feeding heavily on grubs or adult beetles. European tests revealed no difference in taste of eggs from grub-fed hens and others; in fact, the former had better yolks "for thickening and were worth three of the others to color sauces." The only unfavorable result was "in the case of dried beetles mixed with bread and potatoes, which proved too exciting for the older fowls."

Davis notes objections raised to the use of hogs, mainly to pasturing on sod land: l) Need for hog-tight fences - Davis believes the cost is quickly recouped through the value of the grubs as feed; 2) Rooting up of pasture land - to which Davis says the overturned sod reseeds itself the following season with no ill effect other than a roughing of the surface, which is of little significance; 3) Possible infection with the giant thorn-headed worm, *Echinorhynchus gigas*, an intestinal parasite of hogs, and of which the white grub is an intermediate host. According to Davis, there is no problem in fields where hogs have not pastured within the past three years. Brood sows should be prevented from running in fields that are likely to contain infected grubs and in which hogs have pastured within the previous season or two. Less care is needed relative to hogs being fed for market as they will probably be slaughtered before the worms become damaging. Davis (pp. 23-24, his Fig. 14) provides a three-year schedule for using hogs to harvest grubs and prevent crop damage. Davis states that there is an average of 106,680 grubs per acre in infested areas, and that their weight during the fall of their destructive season averages 1 gram (adults weigh slightly less); thus an infested acre contains approximately 235 lbs of grubs. Davis (pp. 3-11) provides information on taxonomy, life cycles, etc.

Finally, Davis presents the results of proximate analyses (% of fresh weight) of *Lachnosterna* grubs and beetles (p. 20):

	Grubs	Adults
Moisture	70.0	60.4
Crude fat	3.1	4.0
Crude protein	11.1	20.1
Crude fiber	1.6	8.7
Crude ash	2.0	1.6
N-free extract (carbohydrates)	2.3	0.3

Cotton and St. George (**1929**, p. 4) summarized the early use of the meal worm, *Tenebrio molitor* (Family Tenebrionidae), as animal feed, stating that it was introduced into Chile solely for rearing the larvae as bird feed. In aquariums and zoological parks, they were in great demand for feeding small birds, amphibians, reptiles, insect-eating mammals, fish and carnivorous arthropods. According to Cotton, a fish-bait vendor told him that "he could use 'half a billion' of them [mealworms] annually." Cotton cites early references, as early as 1721, on their use as bird feed in Europe and summarizes his own extensive biological studies on rearing them.

Fleming (**1968**, pp. 3-4) notes that many native birds and mammals feed readily on adults of the Japanese beetle, *Popillia japonica* Newman (Family Scarabaeidae). He cites a U.S. Bureau of Biological Survey report in which stomach contents of 16 of 31 species of birds examined contained beetle remains. Grackles ate more than other birds; all 29 grackles examined had eaten beetles and the beetles constituted 66% of their stomach contents. Chickens, turkeys, ducks and guineas feed readily on beetles and these along with the grackle, European starling, crow and gull (*Larus* spp.) dig up and devour large numbers of grubs in heavily infested areas, especially when fields are being plowed and grubs are close to the surface in grasslands. Among native mammals, skunks are the most diligent predators of the *Popillia* grubs. The common toad (*Bufo lentiginosus*) eats many beetles. Hogs have long been known to gorge themselves on grubs.

Fleming cites three sources in stating that proximate analyses of the beetles revealed 67.4% moisture, 22.1% protein, 2.1% fat, 1.5% ash, 6.6% crude fiber, and 0.3% nitrogen-free extract.

With space flight as well as planet-side food production in mind, **Kok** (**1983**) proposes to apply automated industrial technology wherein substrate is converted to insects in a manner similar to single cell protein production. He explores several possible system types and operating methods using the concept of packed beds for insect incubation, growth and reproduction and concludes that the concept is feasible. The drug store beetle, *Stegobium paniceum*, is the experimental animal used in the investigation.

Kok et al (**1988**) report that it is technically feasible to mass-produce insects for human consumption by using industrial methods. The test organism was *Tribolium confusum* (the confused flour beetle). The authors describe a semi-continuous process based on the use of a single, batch-fed plug flow reactor and three basic unit operations. The material passed through the reactor in four streams of small, segregated batches with a phase lag of 2 days between them. The reactor performed four major functions corresponding to the four streams; 1) feed conditioning, 2) feed conversion, 3) dormant stage incubation (eggs, pupae) and 4) propagation (egg production). The process consists of two major "cycles," conversion and propagation. The three unit operations are sifting, air classification and solids mixing. Bread, sphagetti sauce and hot dog weiners were prepared with the product pupae. These were found to be palatable by volunteer consumers.

Kok et al (**1991**) report the results of opportunistic sampling of the system described in previous papers. Samples were analyzed for moisture, ash, protein and fat, and mass balances were then calculated for these components. Carbohydrate was found by difference. The objectives of nutrient incorporation and fat generation were partially met, but overall yield of the process was rather low, according to the authors. "Process losses were dominated by losses incurred during the organism propagation cycle; nitrogen was lost in organism wastes such as larval exuvia." Results of the study will be used in designing a second generation process.

Weissling and Giblin-Davis (**1995**) tested several artificial diets as alternatives to decomposing pineapple for culture of *Rhynchophorus cruentatus* (Fabr.) larvae. The most suitable diet for larval growth and survival was a combination of canned pineapple, oats, sucrose, molasses, brewers yeast, Wesson's salts, vitamins and preservatives. Poor growth and survival were obtained on diets not supplemented with brewers yeast. It was found that larvae would construct a cocoon only when placed in sugarcane stem. Sugarcane appeared to contribute little to continued growth of maturing larvae and probably is nothing more than a source of fiber for construction of the cocoon. Although the motivation for this study pertained to the vector potential of *R. cruentatus* for the red ring nematode, *Bursaphelenchus cocophilus*, the authors state:

> . . . although we are aware of no human consumption of *R. cruentatus* larvae in the U.S., larvae of *R. palmarum, R. phoenicis*, and *R. ferrugineus* . . . are considered delicacies by some [in Africa, Asia, Latin America]. The culture of *R. cruentatus* on artificial diets could be a potential advancement in developing a niche for consumption of our indigenous species by palm weevil gourmets or feeding burrowing owls in captivity.

The authors note that, unlike some other *Rhynchophorus* species, *R. cruentatus* is not considered a major pest of palms, but it will attack transplanted or otherwise stressed ornamental palms; in Florida it is sympatric with the native cabbage palmetto, *Sabal palmetto*, which, because of its low cost, natural abundance, and high transplanting survivorship, is often used as mature specimens in landscaping.

Diptera

In situations where poultry manure is not usable as fertilizer in the immediate vicinity where produced, its disposal poses problems of odor, fly production and N contamination of soil and water. Various fly species have received experimental attention for their ability to recycle poultry and other animal manures into useful feed products for poultry and livestock. **Hodge** (**1911**) calculated that a pair of house flies, *Musca domestica* L. (Family Muscidae), starting in April could produce enough progeny by August, if all survived, to cover the earth with a layer of flies 47 feet deep. Although, as pointed out by **DeFoliart** (**1975**), this is an ecological absurdity, it does indicate the tremendous reproductive potential of some insects. **Lindner** (**1919**) appears to have been the first to suggest that house fly larvae might be used to recycle organic wastes, human waste specifically, to produce protein and fat as a useful byproduct.

Rodriguez and Riehl (**1959**) conducted an experiment to determine whether cockerels could provide fly (*Musca domestica*) control in manure under chickens housed in wire cages off the ground. They described their rationale thusly:

> Young chicks instinctively scratch and search every bit of surface within their reach constantly and industriously looking for food. If growing chicks were allowed to scratch in the droppings under the wire cages, would their activities control flies? If they did, what management practices would be useful in obtaining optimum performance?

Impressive control of *M. domestica* breeding was demonstrated in a flock of 200 chickens using one cockerel per 10 hens in cages. In four instances larvae were found in spots where the manure was very wet and hard for the chicks to work; no pupae were ever found, however, suggesting that larvae which the chicks did not find in the manure were caught as they left to seek dryer areas for pupation.

In followup research, **Rodriguez and Riehl** (**1962**) demonstrated control of flies (*M. domestica*) by use of cockerels on commercial poultry ranches in southern California. They reported reductions to zero, in some cases, of fly larvae and pupae in chicken manure under cages with a raised wire mesh floor when cockerel chicks were released on the ground. Control was maintained with ratios of 20 to 100 hens in cages per one cockerel on the ground. The authors describe management practices favorable to successful fly control by the chicks. In the laboratory, baby chicks only 1-2 days old were found to peck instinctively at larvae and pupae although they were unable to pick them up. At 3 days of age the chicks ate 100 larvae or pupae per chick per day and by 15 weeks of age were averaging 8,000 or more per day. The consumption of the flies (200 g/day) was higher than the consumption of mash or grain on a free-choice basis. Under ranch conditions, feed was supplied in the evening for the first few days but not thereafter unless fly breeding was completely eliminated. At a rabbitry with 175 rabbits, control of fly larvae and pupae was obtained with one cockerel per five rabbits.

Calvert and colleagues at the U.S. Department of Agriculture were one of two groups which began research in the late 1960's on the use of *M. domestica* for recycling poultry manure into a high-protein feedstuff for poultry. **Calvert et al** (**1969a**) analyzed pupae produced in CSMA fly medium and found a crude protein content of 63.1% and fat content of 15.5% (Table 1; see authors' Table 1). Amino acid analysis indicated a protein quality similar to that of meat and fishmeal; fatty acid analysis showed a pattern similar to that of some fish oils, although the pupal fat content was higher. Ash content was lower than that of fish meal. When house fly pupae were incorporated into a practical chick starter diet, replacing soybean meal, the chicks gained significantly more weight than chicks fed the soybean meal diet during a two-week experiment. The increase in weight gain was due to an increase in feed consumption as feed-to-gain ratios were similar in the two qroups.

Relative to recycling poultry manure, **Calvert et al** (**1969b**) reported in a brief abstract that fresh hen excreta will support a density of 3 pupae per gram at temperatures of 23 to 26 C, and at this density the feces loses about 20% more moisture than feces without pupae. With a moisture content of only about 46%, the feces is loose, crumbly in texture, and essentially odorless.

Calvert et al (**1970**) presented data to support the seeding rate of 3 eggs per gram of fresh excreta as the optimum seeding rate, and described equipment designed to simplify collection of pupae from the processed excreta. A seeding rate of 1.5 eggs per gram of excreta produced the largest pupae (ave. of 16.5 mg), highest survival (85.1%), and a total pupal weight of 4.23 g from 200 g of excreta in 8 days. A seeding rate of 4.5 eggs per gram of excreta yielded the smallest pupae (10.0 mg), lowest survival rate (44.4%), and lowest total pupal weight (3.87 g) (although this seeding rate did result in the greatest loss of moisture and thus weight, as well as nitrogen reduction in the fecal samples). At a seeding rate of 3 eggs per gram of excreta (the rate selected as best), pupal weight averaged 12.0 g, survival 66.4%, and total weight of pupae 4.55 g.

Regardless of seeding ratio, odor was reduced to an unobjectionable level within 4 days, and the excreta were reduced to an essentially odorless, friable material within 8 days. The investigators suggest its use, with additional drying and pelleting, as a soil conditioner. The pelleted material was found to disintegrate rapidly with the addition of water, and without renewing the obnoxious odor of the fresh excreta.

Morgan et al (**1970**) re-described and illustrated the pupal harvest apparatus described previously by Calvert et al (1970) (Fig. 1; see authors' Fig. 1). Fresh poultry feces, 10-12 lbs, were placed in the center section of the top box to a depth of 2.5 to 3 inches; the narrow side sections served as air vents for release of the ammonia accumulating below. The device was kept lighted from above to prevent the negatively phototactic larvae from wandering upward in search of pupation sites. By the sixth day, at 68-80° F, most of the larvae had passed through the 1/8-inch hardware cloth floor to the tray below and wriggled through the l/16-inch fiber-glass screen to the solid floor to pupate. The few particles of fecal material that dropped through the hardware cloth were retained on the fiber qlass screen.

Morgan et al note that the excreta of White Leghorn laying hens average 0.25 to 0.40 lbs/day. Thus, the daily production of 100,000 layers ranges from 12.5 to 20 tons and creates an enormous disposal problem resulting from odor and water pollution. Morgan et al believe that, from the excreta of 100,000 hens, 500 to 1,000 lbs of pupae can be produced daily while reducing the excreta to a semi-dry, crumbly waste suitable as a soil conditioner.

Calvert et al (**1971**) conducted analyses and feeding trials to determine the value of newly emerged house flies as a protein source for chicks. The fresh flies contained 69% moisture; the dried material contained 75% protein and 7% fat. In feeding trials to 3 weeks of age, the fly meal slightly improved chick growth and there was little difference in feed/gain ratios compared to chicks fed a soybean meal diet. Thus, the adult house fly is also a good protein source for the young chick. These investigators also tested the digested manure for chick growth, but growth was substantially less than for chicks fed the soybean meal diet.

The second group initiating research on the house fly in the late 1960's was at Colorado State University. In a brief abstract, **Miller and Shaw** (**1969**) state that of five species tested for their ability to grow and reproduce in fresh poultry manure, *Musca domestica* and *Muscina stabulans* (Muscidae) were most promising. *M. domestica* developed from egg to pupa in 56 days at 37° C. The larvae removed about 80% of the organic matter from fresh poultry manure, and reduced the moisture content of the manure from 75% to 50% in 5-6 days. No experimental methods are described in the abstract.

Miller (**1969**) discusses the disposal problem, pointing out that fresh manure is heavy, containing about 75% water, and that the labor needed to move it from points of accumulation prohibits its use as a fertilizer. Such manure accumulations offer breeding sites for wild flies, thus creating a sanitation problem. Miller briefly describes methods of managing the fly breeding colony and harvesting pupae, presents tables of data on proximate and amino acid analysis and mineral content of dried fly pupae, weight gains and feed efficiency on broiler diets containing fly pupae, and analysis of fresh and digested manure, but gives no experimental methodology.

Leinati et al (**1971**) reported that infestations of *Hypoderma* sp. (Hypodermatidae) in the backs of cattle on mountain pastures can be reduced by allowing cattle and poultry (chickens and turkeys) to graze together on the same pastures. The poultry devour grubs after they drop to the ground for pupation.

Teotia and Miller (**1970a,b**) presented brief abstracts of work that was published in full later. **Teotia and Miller** (**1973a**) describe methods of managing the breeding colony, conducting larval density, humidity and temperature studies, pupal harvest (by flotation), and production under caged layers. They found the best seeding rate to be 3 g of fly eggs per 4 kg of fresh manure (Table 2; see authors' Table 1]) at 27 C and 41% RH. This seeding rate resulted in the highest total weight of pupae harvested (76 g), highest percentage of manure lost in digestion (51.3%), and lowest weight of manure harvested (1,949 g). It took 8 days at 27°C and 41% RH. At these temperature and humidity conditions, moisture in the manure was reduced from 78.5% to 55.0% by the aerating action of the larvae and decomposition of the manure. Teotia and Miller also used fly eggs and/or larvae seeding to digest the manure under caged birds. This worked fairly well, but temperature must be kept above 20 C or larval development is inhibited.

Teotia and Miller (**1974**) conducted proximate and amino acid analyses on house fly pupae and obtained values similar to those of Calvert et al (1969) except that fat content was lower and ash content higher than in the former study. These differences may have been due to the different rearing media employed, Teotia and Miller rearing their larvae in poultry manure while Calvert et al used CSMA fly medium. In the feeding trials, day-old single comb white leghorn chicks were fed to 4 weeks of age on house fly pupae with or without addition of a B vitamin and trace mineral supplement. Final body weights and feed/gain ratios of chicks fed the experimental diets and the soybean meal control were not significantly different. Unfortunately, the fact that the house fly pupae were merely substituted for soybean meal made the diets neither isocaloric nor isonitrogenous, which makes a direct comparison impossible. It appeared, however, that the pupae were a good source of B vitamins and trace minerals. The authors also conducted proximate and mineral analyses of fresh and digested manure. In feeding trials with manure containing pupae, chick growth was comparatively poor on the digested manure/pupae mixture.

Teotia and Miller (**1973b**) conducted a second set of feeding experiments in which the flaws in the first experiments were corrected by adjusting the levels of the other dietary ingredients so that the experimental and control diets were isocaloric and isonitrogenous. Also, fast-growing broiler chicks were used which should be more sensitive in detecting differences in protein quality. Lastly, this trial was of 7 weeks' duration as opposed to 4 weeks in the earlier experiments. As before, the experimental diet was not supplemented with a B vitamin or trace mineral mix. After 7 weeks there were no significant differences in weight gain or feed/gain ratios between the two treatments. Unfortunately, the protein content of the diet was kept constant throughout the experiment and since the NRC (1977) requirement for broiler chicks changes from 23% at Day 1 to 18% at 6 weeks of age, the ability of this experiment to detect anything but a major difference in protein quality was compromised.

Miller et al (**1974**) provide a summary table (Table 3; see authors' Table 2) showing results of digestion of fresh poultry manure at a seeding rate of 1.0 g of fly eggs/kg of manure. Approximately 80% of the organic matter was used by the larvae during their development. About 58% of the moisture was lost while mineral content was not changed. The manure residue contained about 15% protein after pupae were removed. Physically, the manure was somewhat granular and could be dried readily because of the increased surface area, small particle size and improved aeration.

Hale (**1973**) reported that dried larvae of the soldier fly, *Hermetia illucens* (L.) (Family Stratiomyidae) contained 45.2% crude protein and 31.4% ether extract. Amino acid analysis showed the larvae to be higher in methionine (1.9% of crude protein) than either soybean meal or meat scraps (both 1.4%). In a two-week feeding trial, there were no significant differences in weight gained or feed/gain ratio of chicks fed a diet containing either dried *Hermetia* larvae or soybean meal as the major protein source. The chicks fed the soybean meal diet consumed significantly more feed, however. The author speculates on several possible causes for the apparently lower palatability of the larval diet: high content of larval meal (35% of the diets were composed of larval or soybean meal, respectively); somewhat higher fat content in the larval diet (chicks on the soybean meal may have compensated by consuming more total feed); and, higher crude fiber content in the larval diet.

Hale notes that *H. illucens* larvae are large, full-grown larvae averaging about 250 mg in weight compared to about 25 mg for house fly pupae. The larvae are found in a variety of moist situations high in organic matter, such as decaying fruits and vegetables, damp feed grains either ground or whole, and animal wastes in and near animal quarters. About two weeks are required to reach maturity, and the larvae are very "hardy."

Beard and Sands (**1973**) tested larvae of several species of Diptera for their ability to degrade both anaerobic and aerobic poultry manure. They found that all species tested except *Fannia canicularis* (L.) (Family Muscidae) and unidentified species of Sphaeroceridae (small dung flies) failed completely in anaerobic manure. *Fannia* and the sphaerocerids thrived in aerobic manure, but Beard and Sands concluded that their small size and their behavior limit their potential practical value in degrading manure. The house fly, *M. domestica* showed the greatest adaptability for managed degradation of aerobic poultry manure, while larvae of several other species didn't grow well enough to warrant further investigation, i.e., *Phormia regina* (Meigen), *Protophormia terrae-novae* (Robineau-Desvoidy) and *Phaenicia sericata* (Meigen), all of the Family Calliphoridae, and *Sarcophaga bullata* Park (Sarcophagidae).

Beard and Sands provided data on a number of factors affecting degradation of poultry manure by the house fly. 1) Genetic variability offers the opportunity of selecting strains that are better degraders of manure. Seven strains were evaluated on the basis of mean survival-size scores, including two flightless strains, but none were better than the strain already adapted to the laboratory. 2) There appeared to be no difference in fecundity (and therefore dietary protein for egg development) between sugar/manure-fed flies and sugar/milk-fed flies. 3) When offered a choice between manure and dog food moistened with yeast suspension as an oviposition medium, flies discriminated against manure, but in the absence of a better alternative, manure was acceptable. 4) Measured by survival-size score, dog meal-yeast medium was slightly better (significant at 5% level) than manure as a larval development medium. 5) Size-survival scores showed that flies do better (larvae) in fresh than in aged manure. 6) Rate of oxygen consumption is a gross measure of metabolic activity of organisms growing in manure. Oxygen was utilized at essentially the same rate by manure with larvae alone, with microorganisms alone, or with both. 7) Bacteria rather than fungi appear to be the dominant constituents of manure microflora. Some bacteria may be detrimental to larval development while yeasts appear to play a minor role as a dietary source for larvae. 8) Although larval activity reduced N, anaerobic decomposition did also, almost to the same degree. This and the results of respiration studies suggest that larvae share manure nutrients with microorganisms and that reduction of N levels is not solely attributable to larvae. The main contribution of larvae appears, therefore, according to the authors, to be mechanical aeration resulting in increased loss of ammonia, water vapor, and other gases; hence favoring aerobic organisms, eliminating offensive odor, and dehydrating the medium. The authors discuss these and other factors as they interrelate in manure degradation. Pupal harvest by flotation isn't good because it doesn't retain the dry condition of the residual manure. The authors suggest that hens could be used to pick larvae and pupae from the manure.

Papp (**1975**) conducted experiments to determine the economic feasibility of processing pig manure by house fly larvae. Production yields were as high as 8.05% compared to a theoretical maximum of 10%, results considered equivocal by the author.

Chemical assays by **Dashefsky et al** (**1976**) showed pupae of *Musca autumnalis* DeGeer (Family Muscidae) to contain a high percentage of phosphorus, 5.73% of dry weight. In a 15-day feeding trial, the phosphorus was found to be at least 92% biologically available to White Rock chicks, making the pupae at least of the same quality as most of the commercially sold dicalcium phosphate sources. Analysis of dried pupae meal revealed a crude protein content of 46.5%.

Newton et al (**1977**) conducted a digestion trial on 5-week-old barrow pigs to evaluate dried, ground soldier fly larvae, *H. illucens*, as a dietary supplement compared to soybean meal. The larvae were collected from cattle feces and urine slurry. Proximate composition and calcium and phosphorus content of dried larvae was 7.9% moisture, and, on a dry matter basis: crude protein 42.1%, ether extract 34.8%, crude fiber 7.0%, NFE 1.4%, ash 14.6%, calcium 5.0% and phosphorus 1.5%, respectively (see authors' Table 2 for these data and data on digestion trial diets). Apparent digestibilities for the larval meal diet and (in parentheses) the soybean meal diet were: dry matter 77.5 (85.3), nitrogen 76.0 (77.2), ether extract 83.6 (73.0), crude fiber 53.8 (49.2), ash 45.2 (61.7), NFE 84.7 (91.2), calcium 38.9 (39.3), and phosphorus 24.5 (51.3). Values for dry matter, nitrogen, ash and NFE were significantly greater ($P < .05$) for the soybean meal diet than for the larval meal diet. Pigs did not discriminate against the larval meal diet, indicating good palatability. The authors conclude that further studies are needed to determine the optimum levels of larvae in livestock diets. Larvae would be especially valuable for their amino acid, ether extract and calcium content, but because of the high ash and ether extract content might be better utilized at lower levels than those used in these trials. **Booram et al** (**1977**) reported the results of additional investigations on the recycling of swine manure by *H. illucens*.

Calvert (**1977**) reviewed the use of both unicellular organisms and invertebrates for protein production from animal and municipal wastes, including algae, yeasts, fungi, mixed cultures of bacteria, house fly larvae and earthworms.

Ocio et al (**1979**) provided proximate and amino acid analyses of house fly larvae grown in municipal organic waste (MOW). Feed trials were conducted with three diets that were isocaloric and isonitrogenous: 1) standard corn-soy diet, 2) fish meal substituted for some of the soybean meal so that 9% of the dietary protein was from fish meal, and 3) house fly larvae substituted for some of the soybean meal such that the larvae furnished 12% of the dietary protein. There were no significant differences in weight gain or feed/gain ratio in birds from any of the three treatments after 4 weeks.

Abdel Gawaad and Brune (**1979**) tested a mixture (1:1) of dried, ground larvae of *Phormia regina* (Family Calliphoridae) and *M. domestica* as the high-protein source for broilers fed through the fourth week of age. Amino acid compositions of the two fly species were similar (data are given by the authors). Lysine content of the larvae-meal was high, even higher than in fish meal, but methionine was low. There were no significant differences in final weight or feed conversion efficiency of chicks fed the experimental larval meal diet and the control chicks fed the soybean meal diet. The investigators observed a significantly lower weight of feathers in the larval-fed group, which they suggest may have resulted from the low methionine in the diet. As to carcass composition, the dry matter content of the breast muscle and the drumstick of the test animals was significantly greater than in the controls, which the authors attribute to a significantly higher fat deposition, while protein accumulation was lower in the test animals. The ash content in the meat and bones showed no marked difference. In an organoleptic test on the stewed breast meat, no marked effect on color, smell or taste could be detected.

Abdel Gawaad and Brune mention a rearing procedure (not yet published) whereby one pair of flies supposedly produces 190 billion flies from April to September; based on a fresh weight of 0.023 g per full-grown larva, this would total 4.4×10^6 kg fresh weight or 1.2×10^6 kg dry weight, and about 0.6×10^6 kg of protein.

Koo et al (**1980**) conducted studies on the face fly, *Musca autumnalis* (De Geer), reared in cattle manure and allowed to pupate in sand. The authors point out three biological advantages of this insect over the house fly: 1) It's larger in size, face fly pupae averaging .03 g compared to .025 g for house fly pupae; 2) Pupation occurs in 3 days following oviposition at 41°C compared to 5-6 days for the house fly; and 3) Adult house flies are subject to epidemics of infection with the phycomycete *Entomophthoro muscae* while there is no record of face flies succumbing to this fungus. At the conclusion of feeding, face fly larvae, like most other flies, void the intestine and seek a drier location in which to pupate making it easy to harvest the pupae free of the manure in which the larvae have fed.

Proximate analysis revealed 51.7% crude protein in the face fly pupae, which is less than that found in house fly pupae. Crude fat content was intermediate compared to reported values for the house fly while nitrogen free extract and fiber were less than in the housefly. Interestingly, face fly pupae contained 3 times as much calcium and twice as much phosphorus as reported for house fly pupae. In feeding trials using Single Comb White Leghorn chicks, in which dried pupae were directly substituted for soybean oil meal to 4 weeks of age, there was a slight decrease in feed efficiency which the authors attribute mainly to the lower gross energy value of the pupal meal (4.284 kcal/g) compared to the soybean meal used (4.682 kcal/g). Microbial counts of the dried pupae were well below the tolerances for human food as given by Powers (1976). The authors conclude that dried, ground face fly pupae are a suitable source of protein in poultry diets and that, microbiologically, they would be acceptable for human consumption.

In feeding trials with channel catfish and blue tilapia, manually collected black soldier fly larvae (*H. illucens*) from poultry waste have shown promise as a feed ingredient for commercial fish production (**Bondari and Sheppard 1981**). Taste tests showed that the fish fed soldier fly larvae are acceptable to the consumer. The authors note that, because the larvae of this species can be produced from a wide variety of waste materials, "production of larvae on a large-scale basis for fish and animal feed will also have an impact on recycling of waste products."

Tests in an experimental caged layer house demonstrated that soldier fly larvae (*H. illucens*), in addition to offering a potential food source, provide house fly and lesser house fly control and about a 50% reduction in manure volume (**Sheppard 1983**). The rate of self-collection by the larvae indicated that a commercial operation with 20,000 hens could harvest 540 kg of mature larvae per month during the summer.

E1 Boushy et al (**1985**) discuss limitations inherent in the value of dried poultry manure (DPM) as poultry feed and suggest (with a review of the pertinent literature) that the use of organisms to break down the excreta, such as house fly larvae, earthworms, or by means of fermentation, or upgrading by aerobic digestion and oxidation ditch or algae culture are ways of converting the manure to a protein source in animal diets. In DPM only about half of the total nitrogen is true protein, the remainder being in the form of uric acid which cannot be utilised by fowl and may even be toxic at levels above 1.07% in the ration. The low available energy in DPM is also a problem. Relative to biodegradation of poultry manure by house fly larvae, E1 Boushy et al note from literature sources that the digested manure residue and pupae contain a high level of protein but a low level of non-protein nitrogen. Pupal yields are 3.2% of the fresh manure and about 4.0% on a dry matter basis. The authors discuss the technological aspects of the different systems of handling poultry manure, focusing on both the advantages and disadvantages of each. For comparison of earthworms and pupae, the two main sources cited by E1 Boushy (Fosgate and Babb 1972 and Calvert 1977) should also be consulted.

E1 Boushy (**1986**) provides numerous tables and data on the world food supply and diets in the developing countries, stating that diets of the inhabitants are generally sufficient in calories, mainly from vegetable sources, and short in animal protein. Increased consumption of poultry is suggested as the best solution, considering that poultry meat is most palatable and broilers are fast-growing, reaching a weight of 1.5 kg in 7 weeks with a food conversion of 1.8. The total volume of broiler meat produced in developing countries is estimated to be 7 million metric tons per year, providing an estimated consumption of 3 kg per capita per year. E1 Boushy advocates the development of local industries, as opposed to home slaughter, partly because of better utilization of byproducts such as manure and offal, leadinq to the establishment of secondary rural industries.

According to E1 Boushy, poultry in the developing countries produce about 40.3 million metric tons of manure per year, about 26.2 million tons of it from layers and 14.1 million tons from broilers. The use of dry poultry waste as feed for ruminants, aerobic fermentation, or biodegradation of the manure with organisms such as fly larvae or earthworms are ways of upgrading the manure to supply feed products. In the case of house fly pupae, based on a yield of 3.2%, a metric ton of manure can be converted to 32 kg of high-protein feedstuff. This compares to 13.3 kg of dried earthworms per ton. The total of 40.3 million metric tons per year could thus be converted to l.3 million tons of fly pupae.

Glofcheskie and Surgeoner (**1990**) investigated the usefulness of Muscovy ducks in an integrated program for control of house flies (*M. domestica*). In laboratory trials, ducks removed adult house flies at least 30 times faster than commercial bait cards, coiled fly paper rolls, fly sheets, or fly traps. The LT_{90} for ducks in 0.24^{m3} cages with 100 flies was 0.6 h compared to 15.3 h for the most effective commercial device. In pens with calves, ducks survived for test periods of 12 weeks or more without injury or feed supplement, and ingested a mean of 25 flies per 15-min observation period when populations were low to moderate. The observed behavior is innate, suggest the authors, as the experimental ducks had no previous experience with flies, yet fed on them readily even when provided feed *ad lib*. One of the ducks penned with a calf was observed to capture, on average, 23 flies per 32.5 attempts. Two (among several) advantages of ducks were effectiveness against insecticide-resistent flies and elimination of breeding sites by removing spilled feed. The ducks were also more economical than the commercial control devices. The authors estimate that under their local conditions a producer could make a profit of $65 on 10 ducks by selling them at the end of the season, while the other control devices range in cost from $171 to $455 for season-long fly removal.

At a midsize dairy farm that kept unrestrained Muscovy ducks for fly control, the ducks stayed in the vicinity of the barn and interacted well with animals and humans. In addition to feeding on adult house flies, they also picked flies from the lower legs of cows, indicating that they were also feeding on stable flies, *Stomoxys calcitrans* (L.). The investgators caution that ducks cannot be used in commercial poultry operations because of disease hazards.

El Boushy (**1991**) points out that a chicken ranch with 25,000 caged layers produces 2500 kg of wet manure per day or 912.5 tons per year, thus creating a major problem of waste disposal. Dry poultry manure is not, of itself, recyclable as a good feedstuff for poultry because of its low energy and high content of uric acid and non-protein nitrogen, neither of which can be utilized by monogastric animals. Research during the late 1960s and the decade of the 1970s, however, showed that house fly (*Musca domestica*) pupal meal produced by larval biodegradation of poultry manure is of high protein quality. In addition, digestion of the manure by larvae converts it into an odorless, loose, crumbly product that can be easily dried and used as a feedstuff. Unfortunately, no practical large-scale method of separating the pupae from the digested manure residue has been found. El Boushy suggests then that the most practical procedure is to produce a mixture of pupae and manure residue, thus upgrading the latter to reasonable feedstuff quality. He describes how this could probably be economically accomplished with equipment that is already in practical use on many large poultry farms.

Studies on the soldier fly, *H. illucens*, appear to have solved the problem of efficient harvest of pupae from manure under caged layers (**Sheppard 1992, Sheppard et al 1992**). This non-pest species is proving to be an excellent manure management agent that can produce large quantities of high-quality animal feedstuff, almost completely prevent house fly development and reduce manure residue volume by 50%. Prepupal soldier flies are self-collected as they crawl out of the manure basin seeking pupation sites. They crawl up a 40° slope on one wall of the basin, into a 1/2 inch slit in a 15 cm diameter PVC pipe at the top of the slope, then crawl to a container at the end of the pipe (in the experimental facility, they negotiated a 12-meter length of pipe). The authors estimate that the value of the dried larval feedstuff produced, savings in the cost of insecticide and manure removal and surface application would net a small 20,000 hen egg producer an extra US $7,360. They state that the system should easily adapt to swine waste management, and that soldier flies could be used to degrade many other organic wastes.

In a second report on use of Muscovy ducks for fly (*M. domestica*) control, **Glofcheskie and Surgeoner** (**1993**) found that, in fly-proof calf pens, one duck per pen reduced adult fly numbers by 96.8% and larvae by 98.7% compared to pens without a duck. In an enclosed calf room, fly reductions were 84% and 93% compared to times when ducks were not present. In open areas of the dairy, however, which permitted immigration and emigration of flies, reductions were not statistically significant. Ducks reduced fly numbers on animals by 91% in an enclosed swine farrowing room and by up to 86% in an open dry sow house. Female ducks were observed to consume flies up to three times faster than did males. Ducks had access to flies, water and wasted feed, and duck health was maintained in most experiments without supplementary feedings. At the end of the tests, the least valuable ducks were sold for twice their original cost ($4 vs $2), and, in addition, cooperators saved $100 to $300 by not having to purchase fly control chemicals. The authors emphasize that the use of ducks must be considered a supplement to good sanitation. They report that all of the cooperators indicated that they would use ducks in the following season.

In a textbook based on the use of some neglected vegetable and animal wastes as a poultry feedstuff, **El Boushy and van der Poel** (**1994**) include a section on Dried Poultry Waste under which they discuss biological conversion of layer manure by means of house fly larvae, earthworms, aerobic fermentation, oxidation ditch and algae.

Sheppard et al (1995) add to information on their manure management system using the black soldier fly. Their Abstract is duplicated below:

Indent margins

A manure management system for laying hens using the black soldier fly, *Hermetia illucens* (L.) converted manure to a 42% protein, 35% fat feedstuff, reduced manure accumulation by at least 50% and eliminated house fly breeding. No extra facility or added energy was required. Mature larvae self-harvested producing a feedstuff as they attempted to pupate. Optimal feedstuff to manure dry matter yield was 7.8%. This insect occurs worldwide in tropical and warm-temperature regions and can digest many biological wastes.

Homoptera

Hildreth (**1830**) described an emergence of *Magicicada* (= *Cicada*) *septendecim* (Family Cicadidae) (the "17-year locust") in 1829 in Ohio and mentions their attraction as food for animals: "Hogs eat them in preference to any other food; squirrels, birds, domestic fowls, etc., fattened on them. So much were they attracted by the cicadae, that very few birds were seen around our gardens during their continuence, and our cherries, etc. remained unmolested."

Marlatt (**1907**) lists more than two dozen species of native birds that feed on the periodical cicada. He states that the English sparrow (*Passer domesticus*) is perhaps its greatest enemy, but several native species neglected other foods when cicadas were available. Fox squirrels eat them and chipmunks (*Tamias striatus*) are very fond of them. Cicada remains have been found in black bass, blue catfish and white sucker. Marlatt cites a John Bartram that hogs rooted up the ground a foot deep in search of cicadas and he quotes a Dr. Potter that great numbers are "devoured by hogs, squirrels, all kinds of poultry, and birds, which live and fatten on them." Dogs become fond of them, according to a Dr. Phares (Marlatt, p. 104) who also reported that they were "said to have killed a few hogs in Amite County" in 1859.

Cicadas can be collected by hand if it is done early in the morning or in late evening when they are somewhat torpid and sluggish. Marlatt (pp. 141-142) states that if collecting is "undertaken at the first appearance of the Cicada and repeated each day, the work of control will be facilitated by the fact that most of the insects will be on young trees and within comparatively easy reach." Work for the protection of nursery stock in Pennsylvania is cited in which more than 1,000 cicadas were collected per day per collector. Despite the collection of 70,000 cicadas over a period of more than two weeks, 05% of 240,000 peach trees were lost.

Hymenoptera

In the Prairie Provinces of Canada, Alberta, Manitoba and Saskatchewan, because of the uncertainty of winter survival of honeybee colonies, the bees are killed off in the fall and restocked in the spring. **Hocking and Matsumura** (**1960**), of the University of Alberta, reported that, at the time of killing, colonies may contain from 1/2 to 5 lbs. of mature capped brood (larvae/pupae), and they estimated that there are 132 metric tons of this bee brood available annually. The brood is a rich source of vitamins A and D, and analysis revealed a protein content of 15.4% and 18.2% for mature larvae and pupae, respectively, on a wet weight basis.

When brood was prepared by either shallow frying in butter or deep-fat frying in vegetable cooking fat and tested by a panel of Canadians, "Most reactions were favourable and some were eulogistic; initial prejudice proved easier to overcome than we had expected. When the tasters were asked to compare the material to some more familiar food, those most commonly mentioned were walnuts, pork crackling, sunflower seeds, and rice crispies. In a later, larger taste test, deep-fat fried, butter fried, and baked preparations were highly rated while smoked, pickled, and brandied were much less preferred. There was a highly significant difference of opinion (statistically) between men and women tasters regarding the three best preparations, the men ranking deep-fat fried first and the baked third, and the women reversing this. As described by Hocking and Matsumura, cooking takes about 1 minute; the pupae swell up, turn crisp and a golden brown color, and retain their form and integrity well.

Gary (**1961**) investigated aspects of harvesting bee brood as food. To insure uniformity of larval age at harvest time, brood rearing was concentrated in certain frames by confining queens in frames having queen excluder walls. Every fourth day the comb filled with eggs was removed from the cage and replaced by an empty brood comb. Brood was allowed to develop until most of the larvae were capped (9-11 days). Cells can be uncapped with a thin serrated knife, and larvae are extracted easily and efficiently by spraying the comb with one or more jets of water. Larvae are removed from both sides of the comb and allowed to fall onto a cloth filter such as cheesecloth. After the water is shaken from the cells, the dark empty brood combs can be returned to the queens. The queens prefer them and they encourage maximum egg production. The author states that it is possible to harvest at least one pound of larvae per week from each producing queen.

Ryan et al (**1983**) evaluated adult honey bees (*Apis mellifera* L.), collected after honey harvest in Canada, as a raw material for protein extraction. Fluidized bed dried bees were 36.3% of their fresh weight, vacuum dried bees were 33.5% of fresh weight. An average of 2.14 kg of fresh bees, thus equivalent to 0.717 kg of vacuum dried adults, were removed per colony. The proximate composition of the dried bees was 49.8% crude protein, 7.54% total lipid, 27.1% sugar and 11.1% chitin. As approximately 20% of the bees were not recoverable, being wedged in the comb or contaminated with debris, the investigators estimated that each discarded colony contained the equivalent of 0.879 kg of vacuum dried bees composed of 0.440 kg crude protein. Several factors contributed to variations in the quantity of protein precipitated, but the authors note that these factors would all be present in large scale protein recovery operations. The average quantity of precipitate recovered was 18.1 g dry weight/100 g fresh bees. The precipitate was 66.3% crude protein, 9.4% total lipid and 7.9% ash.

Ryan et al separately extracted heads, thoraces and abdomens of the bees and observed qualitative differences in the color and odor of the precipitates. Amino acid analysis of the three protein fractions found all of them nutritionally deficient in the sulfur-containing amino acids. Chemical scores relative to whole egg protein (FAO 1970), calculated by the methodology of Oser (1951), were found to be 77 for bee heads, 84 for thoraces and 81 for abdomens. These compare with the score of 88 reported by Oser for beef and fish muscle protein and of 80 for yeast. Tryptophan was not included in the analyses by Ryan et al, but they state that it is not expected to be limiting and adequate tryptophan would elevate bee scores approximately 2 points each. Also, whole body scores will be greater than the component scores as different amino acids reduced scores of the separate parts.

Ryan et al cite 1981 Canadian statistics that there were 607,800 honey bee colonies in Canada. Relatively few of these colonies are overwintered, most of them being destroyed after the honey harvest each year (for example, 123,000 of the 160,000 colonies in Alberta in 1980 were not overwintered). In combining their data on adult bees with those of Hocking and Matsumura (1960) on bee brood, Ryan et al estimate harvest values of 3.6 kg fresh bees and brood per colony. At 607,800 colonies in Canada in 1980, they estimate that the potentially harvestable production of bees and brood amounted to a maximum of 2.2 x 10^6 kg fresh weight.

In tests involving rat feeding trials, **Ozimek et al** (**1985**) studied the nutritive value of protein obtained after alkaline extraction from whole adult honey bees. Whole dried honey bees contained 56.8% crude protein (N x 6.25) and 11.1% chitin or 52.0% when corrected for the nonprotein N in the chitin; the protein concentrate contained 64.2% crude protein and no chitin. Corrected for non-protein N in chitin, the apparent protein digestibility of whole dried bees increased from 62.1% to 68.5% and the true digestibility from 71.5% to 79.8%. The true digestibility in the concentrate was 94.3%. In addition to the increased digestiblity, the protein quality of the concentrate was higher than that of whole dried bees as measured by amino acid availabilities (Table 4; see authors' Tables 2 and 4), PER (protein efficiency ratio), and NPU (net protein utilization), as well as by an increased content of some of the amino acids. According to the authors, the absence of chitin in the protein concentrate is probably the major reason for its superior quality compared to that of whole dried bees, as chitin is indigestible and of no nutritional value to monogastric animals (see Lovell et al 1968).

Ozimek et al also calculated the chemical score of the whole dried honey bees and the protein concentrate in relation to the amino acid content in egg protein (see Block and Mitchell 1946; FAO 1970, in Chapter ?) and also a "relative chemical score" which takes into account the availability of the individual amino acids and is therefore a more accurate prediction of protein quality (Table 5; see authors' Table 5).

Thoenes and Schmidt (**1990**) were able to collect 100 g of larvae/10 min. by using a 500 ml plastic laboratory wash bottle to "wash" the cells with a thin stream of water. Larvae of all sizes readily wash from the cells, less than 1% were damaged and the method can be used in the field as well as the laboratory. It would be necessary to uncap cells to obtain mature larvae and pupae. The method is presumably effective for removing drone larvae although the authors do not so state.

Lepidoptera

Landry et al (**1986**) provided proximate and amino acid analyses on larvae of six species in three families: Family Noctuidae included the armyworm, *Pseudaletia unipuncta* (Haworth), the southern armyworm, *Spodoptera eridania* (Cramer), and the fall armyworm, *Spodoptera frugiperda* (J.E. Smith); Family Saturniidae included *Callosamia promethea* (Drury) and *Hyalophora cecropia* (L.); and the Family Sphingidae included *Manduca sexta* (L.). The noctuid larvae ranged between 54% and 58% crude protein on a dry weight basis (Table 6; see authors' Table 1). The fat, and thus energy content was higher in the larvae than in conventional protein supplements. The extremely high fat content in *S. frugiperda*, however, which were fed on an artifical diet, probably reflects the diet and the fact that not all larvae were able to clear the gut before they were harvested. In the saturniids, crude protein was 49.4% in *C. promethea* and 54.7% in *H. cecropia*. Fat content was similar to that found in fish and meat supplements. The sphingid, *M. sexta*, contained 58% crude protein and a very high fat content whether reared on artificial diet or on fresh plant material.

Amino acid analyses of the larvae indicated them to be marginal or somewhat low in methionine-cysteine and arginine, especially when reared on fresh plant material as opposed to artificial diet. In chick feeding trials to 18 and 21 days of age, involving the saturniid and sphingid larvae in practical diets, there were no significant differences in weight gain or feed/gain ratio in chicks fed the corn-caterpillar diets compared to chicks fed a corn-soybean control diet.

In an article entitled, "Grizzlies come back. By relearning old behavior, the great bears may yet avoid extinction," author **Daniel Glick** (**1992**) describes studies by Steven and Marilynn French showing that cutworm moths are an important food of grizzly bears in the Absaroka Mountains east of Yellowstone National Park in Wyoming. The Frenches observed bears (*Ursus arctos horribilis*),
more than 100 totally, feeding on the moths above timberline. In a study on bear feeding ecology in Glacier National Park, Montana, **White and Kendall** (**1993**) found nine moth aggregation sites in the alpine regions of the park. Moths identified from two of the study sites all proved to be *Euxoa auxiliaris* Grote (Noctuidae). Moths collected in mid-July 1992 averaged 24.4% protein and 34.4% fat; mid-August collections averaged 18% protein and 35.4% fat. Bear use of moth aggregation sites lasted at least from July 12 to September 3 in 1992, and 67% of bear activity on the talus slopes was directed toward moth feeding. All bears were grizzlies, no black bears were observed. Several species of birds also fed on the moths.

The moth has an interesting life cycle. It undergoes its development in the Great Plains where the eggs, about 2000 per female, are laid in the soil in the fall. The larva, which has a total of seven instars, is in the first or second instar when it enters diapause. It resumes feeding in the spring on plants such as alfalfa or small grains. The larval period varies depending on temperature and location but may be as long as 25-32 days in Kansas and 43-63 days in Montana. Pupation is in underground cells. The adult moths emerge in early summer and migrate westward into the Rocky Mountains where they congregate above timberline. The moths occupy the interstitia of talus slopes during the day and feed nocturnally on nectar from alpine and subalpine flowers. The return migration to the plains occurs in the late summer or early fall. White and Kendall mention several areas in the Rocky Mountains of Wyoming and Montana where grizzlies are known to feed on cutworm moths and other alpine insect aggregations. In the Mission Mountains, grizzlies feed not only on *E. auxiliaris*, but also on ladybird beetles (*Coccinella* and *Hippodamia* spp.).

Orthoptera

Glover (**1875**, pp. 138-140) suggested that some way should be found for using the devastating hordes of western grasshoppers (Family Acrididae) as a substitute for manure or drying them as feed for hogs and fowl. He states that turkeys, ducks and other fowl are useful in destroying them, and "a large flock of turkeys will soon clear a field of these pests." Also described are "hopperdozers" and various specialised nets for harvesting grasshoppers.

Packard (**1878**, p. 441) described how the African locust (Acrididae) is used as bait for the sardine fishery (see under Algeria), and suggested that should a similar need for bait arise on the Atlantic or Pacific coasts of the United States, large quantities of fish-bait could be prepared by western farmers in locust years.

Whitney (**1892**; vide Wakeland 1959, p. 42) wrote, relative to the preying of gulls on the Mormon cricket, *Anabrus simplex* (Haldeman) (Family Tettigoniidae), and particularly the deliverance of the early Mormon pioneers in the Salt Lake Valley in 1848:

> They were saved, they believed, by a miracle . . . Just in the midst of the work of destruction, great flocks of gulls appeared, filling the air with their white wings and plaintive cries, and settled down on the half-ruined fields. At first it seemed as if they came but to destroy what the crickets had left. But their real purpose was soon apparent. They came to prey upon the destroyers. All day long they gorged themselves, and when full, disgorged and feasted again . . . until the pests were vanquished and the people were saved. The heaven-sent birds then returned to the lake islands whence they came, leaving the grateful people to shed tears of joy at the wonderful and timely deliverance wrought out for them.

Several other early authors have mentioned the gorging, disgorging, and regorging of gulls upon Mormon crickets.

Walton (**1916**, pp. 14-15) described two kinds of hopperdozers. **McHargue** (**1917**) stated that with suitable equipment for harvesting grasshoppers, they might afford a new high-protein source for swine, poultry, and other livestock rations. He conducted a proximate analysis on dried *Melanoplus* spp. (Acrididae) showing 75.3% protein, 7.21% fat, and 5.61% ash. Amino acid analysis showed the grasshoppers to be high in lysine compared to other sources. Minerals were also analyzed.

Milby and Penquite (**1940**), working in Oklahoma, note that turkey growers have followed the practice of allowing young birds to range for most of their food, with only a feeding of grain at night to induce them to come home to roost. Losses are sometimes high with this system, but according to Milby and Penquite, "good turkeys" are produced. Their food is largely insects and tender green feed. Where grasshoppers are numerous, farmers have used the young turkeys to reduce numbers of the pests and at the same time make a profit on the turkeys. The authors mention that, on the other hand, those concerned with marketing have discouraged this method of management, claiming that it produces "tough, stringy birds with an undesirable flavor when cooked."

In feeding trials conducted by Milby and Penquite, 12-week-old poults were fed the experimental rations for five weeks, containing dried grasshoppers either cooked or not cooked, or frozen grasshoppers. Most of the grasshoppers were immature stages, with *Melanoplus differentialis* comprising more than 60% of the samples, and smaller percentages of *M. mexicanus, M. packardii*, *M. femur-rubrum, M. bivittatus*, and unidentified species. The mixed sample contained: protein 62.8%, fat 18.4%, ash 3.9%, fiber 10.9%, and N.F.E. 4.0%. No significant reduction in growth resulted from feeding the rations containing grasshopper meal, but poults fed grasshoppers required more feed per pound of gain (significance not determined). In flavor tests, two birds on the control diet were judged to be the best, but there were no undesirable flavors or odors in any of the birds.

Wickware (**1945**) reported deaths among turkeys from eating grasshoppers in November near Ottawa, Canada. A moribund turkey, upon autopsy, was found to have the crop distended and full of grasshoppers which proved to be *Melanoplus femur-rubrum* (Deg.) and *M. mexicanus* Sauss., two species very common in the area. Wickware quotes personal communication from H.L. Seamans of the Division of Entomology, part of which was as follows:

> It has been my experience both in Alberta and Montana that gallinaceous birds may be killed by the grasshoppers themselves, particularly where they are eaten in abundance without any appreciable amount of other food being taken at the same time. This occurs most frequently in

> the autumn when grasshoppers are sluggish and easily picked up by the birds without any intervening exercise. In the summer, when the grasshoppers are active and the birds have to work to catch them, they are picking up other food between times and do not get their crops filled with just grasshoppers.
>
> I know that in Montana where farmers collected grasshoppers by the bushel and dried them for winter poultry feed, they had to be very careful to make sure that the feed mixture did not contain too high a percentage of grasshoppers. When this was not observed, turkeys and chickens died quite readily.
>
> Death is apparently caused by the hard parts of the grasshopper, particularly the heavily spined legs, not only irritating but actually puncturing the crop. Some cases were autopsied where severe hemorrhage had occurred in the crop, and always the crop was severely inflamed. There were some cases where the intestine was punctured by grasshopper legs. These conditions were also produced experimentally where poultry were fed for a few days on nothing but grasshoppers.
>
> Non-gallinaceous birds are apparently not affected in any way by feeding an over-abundance of grasshoppers. Ducks and geese seem to be able to eat unlimited quantities with no ill effects. Small song birds frequently feed on grasshoppers almost exclusively but they always clip off the wings and legs before swallowing the insect.

From the above and other research cited, Wickware recommends the feeding of a liberal quantity of mash in the morning during the late fall months to reduce and dilute the results of foraging.

Wakeland (**1959**, p. 43) states that hawks feast upon Mormon crickets and that, "Supervisors commonly follow an unusual assemblage of hawks to guide them to infestations." Many other species of birds and mammals are fond of the crickets, including coyotes, skunks, badgers and rodents, as well as lizards and horned toads (pp. 44-46). Poultry, hogs and dogs also eat them.

In studies on Mormon crickets, *A. simplex*, collected in Colorado (**DeFoliart et al 1982**), proximate analysis revealed a crude protein content of 58% on a dry weight basis (Table 7; see authors' Table 2). Amino acid analysis of crickets indicated that for broiler chicks, methionine, arginine, and tryptphan in that order would be the limiting amino acids (Table 8; see authors' Table 3). In feeding trials, however, practical corn-cricket-based diets produced significantly better growth of chicks to 3 weeks of age than was produced by a conventional corn-soybean-based diet (Table 9; see authors' Table 5). Diet #1 in Table 3 is the corn-soy control, Diets #2 and #3 the corn-cricket diets. Diets 1 and 3 were supplemented with amino acids to bring them up to the levels recommended by the NAS-NRC (1977), and all of the diets were supplemented up to recommended levels for minerals and vitamins, since there were no data on these for Mormon crickets. This supplementation with minerals and vitamins ensured that any differences in growth were dependent on the protein quality of the diet. As shown in Table 9, supplementation of corn-cricket diet #3 with purified amino acids did not significantly increase the weight of chicks feeding on that diet over those on the unsupplemented corn-cricket diet (#2). Some of the difference between Diets 2 and 3 over #1 may have been due to the higher metabolizable energy content of the corn-cricket diets because of the high fat content of the crickets.

DeFoliart et al determined dry weights of cricket life stages over a 3-year period and found that male weights averaged between 0.71 and 0.95 g during each of the 3 years, while female weights averaged between 1.17 and 1.50 g. The mean dry weight for both sexes combined in 1980 was 1.09 g. Cricket densities of 10-20/m^2 are not uncommon, and at those densities, and with an average dry weight per cricket of 1.09 g, a 1 km^2 band totals 11-22 metric tons of high-protein powder. Based on 1981 prices of corn and soybean meal, it was estimated that the wholesale value of crickets in a 1 km^2 band ranged from $3,300 to $6,600.

The above authors (DeFoliart et al) raised several questions relative to possible commercial exploitation of the Mormon cricket as animal feed. First, an unanswered question is whether management practices could be developed that would tend to ensure a reasonably dependable cricket crop, a factor that would be important in gaining access to the market. Secondly, the efficiency of cricket utilization of rangeland vegetation in relation to, or in comparison with, other rangeland livestock production systems would be important. Relative to this, **Cowan and Shipman** (**1947**) had quoted unpublished studies by R.B. Swain showing that cricket food preferences placed them in direct competition with cattle in northern Nevada and other areas where the northern desert shrub type of vegetation prevailed. On the other hand, there was little damage to forage, even in outbreak years, in the grassland types of range in Montana, Wyoming and eastern Idaho. According to **Ueckert and Hanson** (**1970**), in the arid ponderosa pine-bunchgrass community in northern Colorado, crickets were primarily herbivorous but also carnivorous and fungivorous, with forbs contributing about 50% of the diet, arthropods and fungi about 37%, and grasses, clubnoss, and grass-like plants about 13%.

In a follow-up on the study by DeFoliart et al, **Finke et al** (**1985**) used Mormon crickets in purified diets (Table 10; see authors' Table 2) and found that methionine and arginine are colimiting. Adding either methionine or arginine alone did not significantly improve either final weight or feed/gain ratio. In an 8-week chick feeding trial (Fig. 2; see authors' Fig. 1), however, in which Mormon crickets were incorporated into practical diets replacing soybean meal as the major protein source, there were no significant differences in weight gain or feed/gain ratio in the corn-cricket diet compared to the corn-soy control. Final body weights averaged 2095 g on the corn-soybean meal diet, and 1947 g on the corn-cricket diet which were not significantly different.

Nakagaki et al (**1987**) provided proximate, amino acids, and minerals analyses of the house cricket, *Acheta domesticus* L. (Family Gryllidae). Crude protein content was 62.0% on a dry weight basis (5.2% water). The data on *Acheta* are quite similar to those obtained on the tettigoniid, *A. simplex*, amino acid analysis indicating that methionine and arginine would be the lst-limiting amino acids, followed by tryptophan. In chick trials to 3 weeks of age using semipurified diets, however, final weights of chicks fed the experimental diets were not significantly different. Feed/gain ratios indicated, however, that tryptophan may be limiting. In experiments using practical corn-cricket diets to 2 weeks of age, again the addition of methionine and arginine resulted in no significant differences in final weights. There was a significant improvement in feed/gain ratios, however, when both were added (but not when either was added alone). That these amino acids are colimiting is similar to the findings of Finke et al (1985) on the Mormon cricket.

Finke et al (**1987**) reported the results of experiments in which weanling rats were fed diets containing corn gluten meal (CGM), Mormon cricket (*Anabrus simplex* Haldeman) meal (MCM), MCM supplemented with methionine (MCM + Met) or CGM-MCM mixtures as the sole source of dietary protein in purified diets. Animal response (weight or nitrogen gain) was analyzed as a function of nitrogen intake and described by a series of curves using a four-parameter logistic model (described separately by Finke et al). When used for maximum nitrogen retention, the protein sources ranked as follows: MCM + Met > 40 CGM-60 MCM > 50 CGM-50 MCM > 60 CGM-40 MCM > MCM > CGM. When used for maximum weight gain, the ranking was: MCM + Met > 40 CGM-60 MCM > 50 CGM-50 MCM = 60 CGM-40 MCM > MCM > CGM. The rankings of the protein sources when used for weight maintenance or nitrogen equilibrium were similar to those seen for maximum weight or nitrogen gain except that the ranking of MCM changed from fifth to first. The investigators concluded from the results that MCM is a good quality protein source and that methionine is the first limiting amino acid when used for growth but not for maintenance.

Finke et al (**1989**) evaluated the protein quality of three insect sources, Mormon cricket (*Anabrus simplex*) meal (MCM), house cricket (*Acheta domesticus*) meal (HCM) and eastern tent caterpillar (*Malacosoma americanum*) meal (TCM) relative to that of lactalbumen (LA) and soy protein (SP), using both amino acid analysis and a rat bioassay. The amino acid pattern of the three insect meals indicated that methionine should be the first limiting amino acid for growing rats. In the rat bioassay, weanling rats were fed graded levels of the five proteins in purified diets and the response (weight or nitrogen gain) evaluated as a function of nitrogen intake. When used either for weight maintenance, nitrogen equilibrium, maximum weight gain or maximum nitrogen retention, the five protein sources could be ranked in the following order: LA>HCM>MCM=SP>TCM. Relative to lactalbumin, the value of all four protein sources decreased with increasing nitrogen intake. The results indicate that some insect proteins are equivalent or superior to soy protein as a source of amino acids for growing rats. The authors suggest that the low values for TCM may have been related to factors other than protein quality.

Nakagaki and DeFoliart (**1991**) estimated the food conversion efficiency of the cricket, *Acheta domesticus*, when kept at temperatures of 30°C or higher and fed the high-quality diets used to bring conventional livestock to market condition, to be about twice as high as those of broiler chicks and pigs, 4 times higher than sheep and nearly 6 times higher than steers when losses due to dressing percentage and carcass trim were taken into account. High fecundity increases the advantage in favor of the insect. Female crickets lay an average of 1200 to 1500 eggs over a period of 3-4 weeks. By comparison, in beef production four animals exist in the breeding herd per market animal produced, thus giving crickets a true food conversion efficiency some 20 times better than for beef.

Parajulee et al (**1993**) developed a model that simulates the harvest of a pre-determined number of eggs of the house cricket, *Acheta domesticus* (L.) per day by regulating the numbers and ages of adults in the breeding colony. This research was done relative to a mass-rearing system for crickets as food which was being developed at the time by the authors. The system was designed to harvest 6,000 crickets per day, but is expandable depending on the daily production desired. Previously, it had been difficult to seed rearing cages with the proper number of eggs per day without the time-consuming work of daily sorting and counting of thousands of eggs from the oviposition medium.

Insects as Food of Non-human Primates

Suzuki (**1966**) described insect eating, primarily ants and termites, by wild chimpanzees (*Pan troglodytes*) in Tanzania, and cites other studies on the eating of insects by chimpanzees, Japanese monkeys (*Macaca fuscata*) and baboons (*Papio anubis*). Chimpanzees and the monkeys are largely vegetarian. Also cited is an earlier study by Shaller who reported that gorillas (*Gorilla gorilla*) never feed on insects. Suzuki, as had Jane Goodall earlier, observed chimpanzees "fishing" for termite soldiers. The tools used for inserting into the termite holes were about 45 cm long and made from either *Hibiscus calyphyllus* (Malvaceae) or *Acalypha ornata* (Euphorbiaceae). Relative to the former, Suzuki states: "This tree is a kind of small shrub with soft, strong fibrous bark. The chimpanzees stripped the bark from a twig of this tree and made the tool from it. The bark possesses the proper strength as a tool and yet is relatively soft so that termites can easily bite into it. It seems apparent that the chimpanzees selected this effective material." It should be noted that termite fishing is also a practice among indigenous human populations in Africa.

Experimental work by **Cornelius et al** (**1976**) demonstrated that chitinolytic enzymes from the gastric mucosa of the primate, *Perodicticus potto*, are true chitinases, suggesting that some other vertebrates also secrete a true chitinase.

Carpenter (**1921**), using a captive young monkey, undertook a study in Uganda to determine the effect of aposematic (warning) coloration or behavior on the acceptibility and edibility of insects. Insects were presented individually to the monkey, or, in some cases, the monkey was leashed and taken on walks. Carpenter appears to have become quite attached to the monkey (who is designated as M in the daily experiment write-ups), describing him as a "delightful youngster of the abundant grey species of *Cercopithecus*, with a whitish band over the eyes." After determining the range of responses to proffered insects from very tasteful to very distasteful, Carpenter adds, "I may say that the monkey's *facial expression* gives a very accurate indication of whether or not the insect is tasty. Carpenter then relates:

> Once I offered the monkey my closed hand. He came up to see what was inside, and I opened my hand and showed him a beetle which previous experiment had proved to be very distasteful. The monkey literally broke into a broad grin and walked away, evidently taking it as a joke!

The non-aposematic grasshoppers were definitely among the most consistently relished of the insects proffered by Carpenter. He remarks: "The species of monkey used for these experiments eats great numbers of Acrididae; I have often seen them hunting through long grass in the evenings, catching the grasshoppers which rose in front of them." He also mentions that a tettigoniid (katydid), *Conocephaloides mandibularis* Charp., which is esteemed as food by the Baganda of Uganda, "was always found extremely edible by my monkey on L. Victoria, who would eat them until his overfilled stomach rejected them!"

Insects as Food for Zoo Animals

Mealworms, both small (*Tenebrio molitor*) and large (*Xophobas morio*), waxworms (*Galleria mellonella*) and crickets (*Acheta domesticus*) are the insects most commonly fed in zoos and aquaria. In chemical composition studies (**Pennino et al 1991**), percent water, and total N (N x 6.25 = crude protein), crude fat and ash as a percentage of dry matter varied widely. Values for crickets were, respectively: 73%, 10.3%, 19.9% and 4.2%; for small mealworms: 61.2%,7.8%, 23% and 2.5%; for large mealworms: 55.6%, 7%, 44.9% and 8.6%; and for waxworms: 59.7% 5.5%, 56%, and 3.2%. Acid detergent-nitrogen (ADF-N) was determined as a measure of unavailable N (about 7% of total N), and neutral detergent fibre (NDF) as an estimate of chitin (averaged about 20% of dry matter). From these data, the authors discuss true protein values and the nutritional importance of chitin both in animals with, and those without, chitinase activity.

Retinol and *a*-tocopherol content are direct measures of vitamin A and vitamin E activity, respectively (two of the fat soluble vitamins). Pennino et al found that the two marine invertebrates tested, krill and squid, were high in retinol, but concentrations in insects were <2.0 ug/g dry matter, indicating that insects in general may be a poor source of vitamin A. Of the insects analyzed, only honey bees may provide adequate vitamin A levels without need for supplementation. Squid were highest in *a*-tocopherol, with insects ranging from 10.4 ug/g dry matter in male honey bees to 179.3 in cockroaches. Health problems from vitamin E deficiency have not been specifically documented in insectivores, and the authors conclude that levels provided by invertebrate prey in general meet dietary requirements. In a short-term feeding trial (one week) involving crickets and large mealworms, it was demonstrated that the vitamin E content of invertebrates used as feed can be altered by altering the dietary levels of this nutrient (significant only for mealworms). Nutrient data were also obtained in this study on several species of insects and other invertebrates (both wild and commercially obtained) which are not mentioned above.

Dierenfeld (**1993**) points out that insects are a substantial part of, or the entire diet fed to numerous species of amphibians, reptiles, birds and mammals in zoological parks, and she provides an excellent discussion of the specific quantity, quality and adequacy of insect-suppled fat, protein, carbohydrate, vitamins and minerals in meeting the different dietary needs. **Dierenfeld et al** (**1995**) reported that retinol and carotenoid analysis of 10 invertebrates commonly fed in zoos demonstrated low concentrations of vitamin A activity. A variety of carotenoids found particularly in free-ranging invertebrates consuming natural diets implies that insectivores may rely on carotenoid pigments as vitamin A precursors. The investigators obtained clinical and histological data suggesting that specialist insectivores may have low dietary requirements of vitamin A.

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