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Sustainable Agriculture Reviews

Volume 13

 Springer

Editor

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UMR1347 Agroécologie
17, rue Sully
21000 Dijon, France

ISSN 2210-4410

ISSN 2210-4429 (electronic)

ISBN 978-3-319-00914-8

ISBN 978-3-319-00915-5 (eBook)

DOI 10.1007/978-3-319-00915-5

Springer Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013932220

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Printed on acid-free paper

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Leaf-Cutting Ants, Biology and Control

Isabelle Boulogne, Harry Ozier-Lafontaine,
and Gladys Loranger-Merciris

Abstract Leaf-cutting ants (*Formicidae*, *Myrmicinae*, *Attini*) are found on the American continent and in the Caribbean and are known to live in symbiosis with a fungus. Among *Attini* tribe, *Atta* and *Acromyrmex* are the two genera, which commonly depend on fresh plant leaves and other plant material for their fungal garden. Overall, these ants are among the most economically damaging herbivorous species. *A. octospinosus* is classified among the most serious pests of tropical and subtropical America. Due to its foraging activity, it can cause serious damages from 20 to 30 % of crop production. Huge losses were observed in several vegetable and fruit crops, in crop of cacao or citrus orchards and in protected areas where some species may completely disappear due to their endemism. Economic losses due to these ants were estimated at several million dollars per year. Although *Acromyrmex octospinosus* is one of the most important species of leaf-cutters because of its economic impact there is a lack of review in the literature.

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We review here the distribution, biology and different kind of control used and sustainable methods that can possibly help to manage. *A. octospinosus* is found only in Neotropics from Central America to northern of South America, including parts of West Indies. A colony is divided into males, breeding females, or gyne, and three castes of workers: small workers or 'minor', medium worker or 'media' and large workers or 'major'. Pheromones are indispensable supports of social life of *A. octospinosus*. Foraging is conditioned by trail pheromone and takes place along a 'line' involving all castes of the colony. The foraging is divided in several steps. Indeed, the ants cut the plant material, transport it into the nest, lick it, cut it into smaller pieces, chew it, depose fecal fluid on it, cultivate mycelium fragment on this prepared mixture and incorporate it into the symbiotic fungus. Symbiotic fungus, or 'fungus garden', is a Basidiomycete, *Leucocoprinus gongylophorus* (Heim) Moeller. It is the exclusive nutrition of both juvenile stages and the queen and is also a supplement of the adult workers diet. The ant also lives with an actinomycete, *Pseudonocardia* sp. This symbiont grows on the cuticle of all ants of the colony and protects fungus garden against fungal competitors and ants against ubiquitous entomopathogenic bacteria and fungi.

The first techniques used to fight against *A. octospinosus* were mechanical methods which have only local efficiency and do not prevent from the reestablishment of colonies. Synthetic chemical control against *A. octospinosus* began in the twentieth century with a direct chemical control and afterward with toxic baits. The efficiency of these controls was limited but all of them caused severe injuries on environment and human health. This situation has prompted an increasing interest in alternative methods to control this pest. Laboratory and field tests of biological control were performed with spores of pathogenous fungus or ants predators into nest, with fungal symbiont's extract and trail pheromone, with entomopathogenic fungus and nematodes. Most of these methods did not give the desired effect or were not confirmed *in situ*. Biopesticides using insecticidal and fungicidal plants are known to be environmentally safe because of their non-phytotoxicity, biodegradability and renewability. Thus, another alternative to chemical control of *A. octospinosus* has been explored with the insecticidal or fungicidal activities of plants extracts, which showed various effects on both *A. octospinosus* workers and *Leucocoprinus gongylophorus* *in vitro* cultures. These tests showed very encouraging *in vitro* preliminary results and may serve as alternatives to synthetic compounds to develop safer control agents of leaf-cutting ants.

Complex relationships and tripartite mutualism are involved between ants, fungus and actinomycete. All studies investigated only one side management. A tripartite management based on a combination of the three strategies should promote a more efficient integrated control and provide some interesting options for the control of this pest.

Keywords *Acromyrmex octospinosus* • Tripartite mutualism • Tripartite management • *Pseudonocardia* sp • *Leucocoprinus gongylophorus* • Sustainable pest management • Biopesticides

1 Introduction

Leaf-cutting ants are insects of the Family of *Formicidae*, Sub-family of *Myrmicinae* and Tribe of *Attini* that includes 12 genera and approximately 200 species (Weber 1972). They are found on the American continent and in the Caribbean (Fig. 1). The *Attini* are known to live in symbiosis with a fungus. These features are the reason why they are called fungus-growing ants. Among the *Attini* tribe, *Atta* and *Acromyrmex* are the two genera which commonly depend on fresh plant leaves and other plant material for their fungal garden. This is the reason why they are also commonly called leaf-cutting ants (Wetterer et al. 1998). Overall, these ants are among the most economically damaging species causing huge losses in all vegetable and fruit crops, in familial garden and natural areas.

Acromyrmex octospinosus (Reich 1793) has several common names and is known as ‘fourmi manioc’, ‘cassava ant’, ‘fourmi parasol’, ‘parasol ant’, ‘leaf-cutting ant’, ‘fungus-growing ant’, ‘sauba’, ‘bibijagua’, ‘bachaco’, ‘bachacs’, ‘sabanero’, ‘zom-popo’, ‘sauva de matta’, ‘hormiga arriera’, ‘hormiga cortadora’ and ‘fourmi-man’. With *Atta sexdens* and *A. cephalotes*, this ant is one of the most important species of leaf-cutters because of its economic impact (Lewis 1975).



Fig. 1 Geographical distribution of the leaf-cutting ant *Acromyrmex octospinosus*. The ant is present in South and Central America and in the Caribbean and is classified among the most serious pests of tropical and subtropical America. It can cause serious damages from 20 to 30 % of vegetable and fruit crops and losses were estimated at several million dollars per year

Although *A. octospinosus* is considered as an important pest, there is a lack of synthesis of information available on it. The aim of this chapter was to document the distribution, biology and control uses that can possibly be used to manage these leaf-cutting ants.

2 Geographical Distribution

A. octospinosus originated from South America and existed since the Cretaceous. This ant is present on its native continent (Curacao, Venezuela, Guyana, Surinam, French Guyana and Brazil), Central America (Mexico, Guatemala and Costa Rica) and in the Caribbean islands (Cuba, Guadeloupe, Carriacou, Grenada, Trinidad and Tobago) (Weber 1966; Discover Life 2012) (Fig. 1). *A. octospinosus* is thus found only in Neotropics ranging from Mexico to Brazil.

3 Biology and Behavior

A. octospinosus is a social insect whose colony can contain 1,000–20,000 individuals (Lewis 1975). The nests are underground, shallow (rarely beyond 50 cm deep) and often included in natural holes created by rocks, tree trunks or roots. They contain a fungus garden corresponding to the ant fungal symbiont (Weber 1966).

3.1 Reproduction

Males are haploid, winged and have no social function in the colony except fecundation during nuptial flights. They die after nuptial flights. Females are diploid and are differentiated by environmental and genetic factors in breeding females (future queens) or workers (Weber 1966). Breeding females (or gynes) are winged (Fig. 2) until nuptial flight where several males fertilize them. Each inseminated gyne becomes a queen and can lead a colony. Queen loses her wings, nests in the soil and begins to lay eggs. She starts cultivate the symbiotic fungus carried in her infrabuccal pocket. Queen survives thanks to digestion of flight muscles and abdominal fats. First larvae survive thanks to 'trophic' eggs that the queen laid. When first workers emerge, they feed the fungus cultivated by the queen and take over maintenance of the nest, eggs and larvae, leaving to the queen the function of laying (Quilan and Cherret 1978).

The juvenile stage (from egg to emergence) takes about 60 days. Eggs hatch out after 24 h and turn into larvae, which evolve in four stages for the workers and five for breeding females and males. Larvae become nymphs without pigmentation (Fig. 3). Pigmentation occurs gradually during the 18 days of this stage. Nymphs become light colored adults with insecure movements (Weber 1972).

Adult workers are wingless and equipped with eight spines on posterior part of thorax, a feature that is the origin of the species name of this ant. The species shows

Fig. 2 Breeding female or gyne (on the left) and inseminated female or queen (on the right) of the leaf-cutting ant *Acromyrmex octospinosus*. Gynes are winged until nuptial flight where several males fertilize them. Each inseminated gyne becomes a queen and can lead a colony. The queen loses her wings, nests in the soil and begins to lay eggs

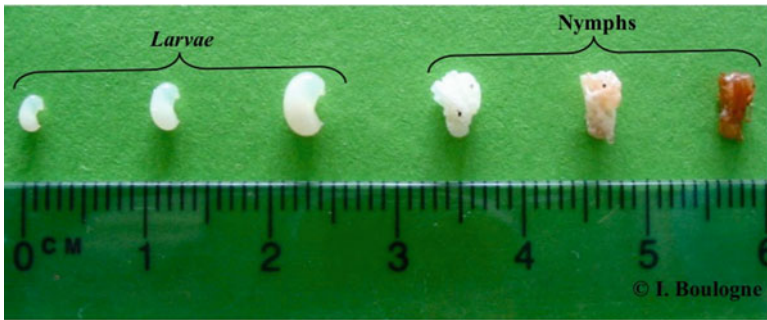


Fig. 3 Larvae and nymphs of the leaf-cutting ant *Acromyrmex octospinosus* at different stages. After the laying, eggs become larvae (in four or five stages), then nymphs without pigmentation and finally light colored adult ants

a high degree of worker size polymorphism with an extensive division of labor among size castes workers. They are divided into three castes (small workers or “minor”, the medium worker or “media” and large workers or “major”) (Wetterer 1991) (Fig. 4). It should be noted that workers may reproduce and lay eggs that develop haploid males. This reproduction is observed in orphan colonies (without queens). These ‘haploid’ reproductions are not observed in colonies with a queen, probably due to the chemical sterility maintained by the queen (Camargo et al. 2006).

Therefore a colony is divided into males, breeding females (or gyne) and three castes of workers (small workers or ‘minor’, medium workers or ‘media’ and large workers or ‘major’). After nuptial flights, fertilized gynes can lead colonies by cultivating symbiotic fungus (carried in their infrabuccal pockets) and laying eggs. After the laying, eggs become larvae (in four or five stages), then nymphs and finally adult ants equipped with eight spines on posterior part of thorax (origin of the ant’s species name).

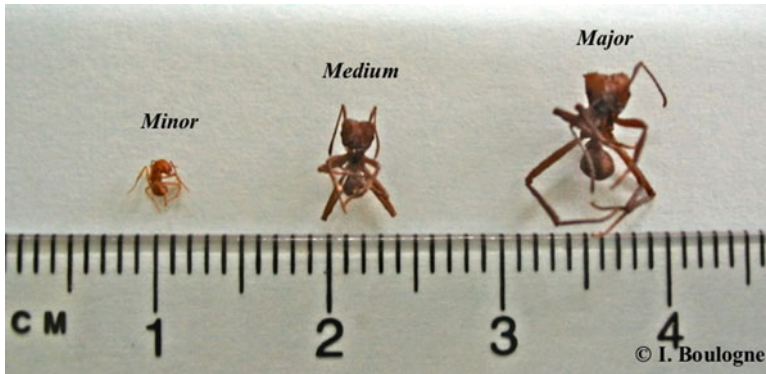


Fig. 4 Small workers or “minor”, medium worker or “media” and large workers or “major” of the leaf-cutting ant *Acromyrmex octospinosus* equipped with eight spines on posterior part of thorax, a feature that is the origin of the species name of this ant. ‘Major’ workers cut and transport plant material to the nest, ‘media’ workers build the nest and defend it against external attacks while ‘minor’ workers take care about the symbiotic fungus, eggs, larvae and nymphs

3.2 Social Behaviour

Chemical signals from *A. octospinosus*, as other *Attini*, are indispensable supports of social life. Pheromones are the main signals emitted by the ants. They play a key role in colony organization. Trigger action pheromones are pheromones of trail and alarm. The latter is secreted by the mandibular gland and consists of 15 compounds, mainly octanone and octanol. The trail pheromone is secreted by the poison gland (or Dufours’ gland) and consists mainly of dimethylpyrrole carboxylate, acetaldehyde and dimethyl-ethylpyrazine (Cross et al. 1982; Evershed and Morgan 1983). Queen pheromone changes the physiology of workers and induce nest attractiveness (Crewe and Blum 1972).

Colony work is distributed based on caste and ant size (Wilson 1980, 1983). The ‘major’ workers are between 7 and 10 mm and are responsible of cutting and transport of plant material to the nest. They also transport eggs, larvae and nymphs inside nest and take part in nest cleaning. The ‘media’ workers are 4–7 mm and are responsible for nest building, expansion, and defense against external attacks. They also clean out waste, rejected plant material and dead ants. The ‘minor’ workers are between 2 and 4 mm and are the most numerous. Their activity is essentially inside the nest where they take care about the fungus. They inoculate mycelium through the plant material with their fecal fluid. They also take care about eggs, larvae and nymphs. Taking care of larval stages includes (Camargo et al. 2006):

- licking larvae bodies, particularly oral and anal regions, in order to clean and sanitize them.
- larvae transport in several locations of nest in order to keep them in the best conditions of temperature and humidity and to protect them from disturbance of the nest.

- larvae nutrition performed by administration of chewing *gongylidia* (mycelium structure defined in paragraph below).
- ingestion of faecal fluid excreted by the larvae to exchange chemical trophalactic messages between larvae and workers. This exchange is probably the way to collect larval secretions containing a chymotrypsin-like endopeptidase (enzyme missing in adult workers) that provide protein degradation.

Hence, pheromones are indispensable supports of social life of *A. octospinosus*. They can be classified into trigger action pheromones (pheromones of trail and alarm) and queen pheromones. Colony work is under pheromones actions and based on ant size: ‘major’ workers cut and transport plant material to the nest, ‘media’ workers build the nest and defend it against external attacks while ‘minor’ workers take care of the symbiotic fungus, eggs, larvae and nymphs.

3.3 Foraging

Foraging is conditioned by trail pheromone. When a major worker discovers an attractive plant material, it returns to the nest, leaving the pheromone on its path. The others workers are oriented along a pheromone gradient. Lengths of foraging trails range between 10 and 100 m depending on colony size (Moser 1967; Fowler 1978).

Foraging is a step process that takes place along a ‘line’ involving all castes of the colony. These steps are described follow (Weber 1966; Camargo et al. 2006):

- cutting the plant material (fresh and fallen leaves, stems, flowers, buds, fruits...) in nature;
- transport of this material in the nest;
- licking it;
- cutting these parts of plant into smaller pieces;
- chewing them;
- deposit of fecal fluid on chewing plant;
- deposit of mycelium fragment on plant substrate previously prepared and incorporation into the fungus garden.

Licking, cutting into smaller pieces and chewing plant material allow fungus to colonize quickly the substrate. Licking also serves to clean and sanitize plant material with antibiotics from the metapleural gland of workers that inhibit the growth of competing microorganisms. Fecal fluid allows a better plant degradation and a better colonization by the fungus thanks to pectinolytic and proteolytic enzymes and free amino acids it contains (Febvay and Kermarrec 1983; Camargo et al. 2006).

It follows that, foraging is conditioned by trail pheromone and takes place along a ‘line’ involving all castes of the colony. The foraging steps are: cut plant material, transport it into the nest, lick it, cut it into smaller pieces, chew it, depose fecal fluid on it, cultivate mycelium fragment on this prepared mixture and incorporate it into the symbiotic fungus.

4 Symbiosis

4.1 Fungi

The fungus symbiont is spongy and breakable and made with plant material and mycelium (Fig. 5). This ‘fungus garden’ has three parts: a superficial and young area called ‘green and black’ zone, a middle one called ‘white’ zone and an oldest basal one known as ‘yellow’ zone. Most authors agree that the symbiont is a Basidiomycete, *Leucocoprinus gongylophorus* (Heim) Moeller (Hervey et al. 1977). At the microscopic level, spheroid swellings located at the apex of the mycelium, the *gongylidia* (grouped into *staphylae*) are specific for this fungus and are one of the recognition criteria (Fig. 6). The *gongylidium* is a differentiated organ protected by a thick wall whose contents a lot of nutrients particularly glycogen (Decharme 1978, 1980). *Gongylidia* are absorbed entirely by the larvae. They provide to them cell walls polysaccharides and cellular contents. Adult ants absorb only cellular contents, and keep mycelium cell walls in their infrabuccal pocket. In this pocket, the fungal cell walls are soaked with saliva, macerated and digested for 24 h thanks to chitinases and chitobiases of labial glands (Febvay et al. 1984). The fungus is the exclusive nutrition of both the juvenile stages and the queen. Fungus’ cellular contents are a supplement of adult workers’ diet. Their main diet is trophallactic exchanges of plants sap.



Fig. 5 *Leucocoprinus gongylophorus*, basidiomycete symbiont of the leaf-cutting ant *Acromyrmex octospinosus*, is made with plant material and mycelium and is the exclusive nutrition of both juvenile stages and the queen and is a supplement of adult workers’ diet

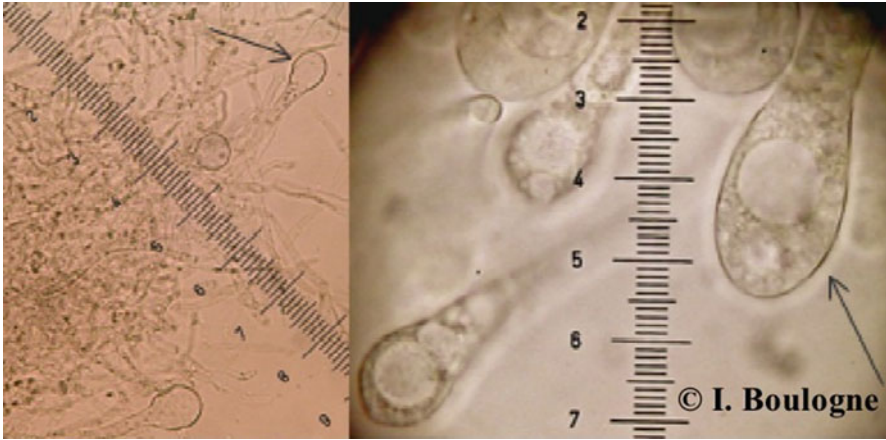


Fig. 6 *Gongylidium* shown by black arrows (grouped into *staphylae*), specific spheroid swellings of *Leucocoprinus gongylophorus*, basidiomycete symbiont of the leaf-cutting ant *Acromyrmex octospinosus*. These *gongylidia* contain a lot of nutrients particularly glycogen, are specific for this fungus and are one of the recognition criteria

Consequently, symbiotic fungus (or ‘fungus garden’) is a Basidiomycete, *Leucocoprinus gongylophorus* (Heim) Moeller. It is spongy, breakable and made with plant material and mycelium. It is the exclusive nutrition of both the juvenile stages and the queen and is a supplement of adult workers’ diet.

4.2 Actinomycete

An actinomycete *Pseudonocardia* sp. grows on the cuticle of workers few days after emergence of insect and entirely covers its body between the 13th and 18th days. This ‘actinomycete coverage’ decreases between the 25th and 30th day for persisting only on latero-cervical area (Camargo et al. 2006). Queens vertically transmit this symbiont to entire colony. This symbiosis acts on fungus garden protection of fungal competitors like *Escovopsis* sp. (Ascomycete) (Fig. 7). It could also have protective action against ubiquitous entomopathogenic bacteria and fungi. The benefit of this symbiosis for the actinomycete is not really known. There is probably a secretion of nutrients on ant cuticle that increase actinomycete growth. This fact might explain actinomycete localization, which depending on ant age. Indeed, young soft ant cuticle might allow establishment and nutrition of actinomycete on the entire young insect body. Older ant cuticle is less soft and actinomycete might only grow on cervical areas (Currie et al. 2003).

Therefore the actinomycete *Pseudonocardia* sp. (vertically transmitted by queens) grows on the cuticle of all ants of the colony. This symbiont protects fungus garden against fungal competitors and ants against ubiquitous entomopathogenic bacteria and fungi. The exact benefit of this symbiosis for the actinomycete is not really known.



Fig. 7 Nests of the leaf-cutting ant *Acromyrmex octospinosus* where *Leucocoprinus gongylophorus* the basidiomycete symbiont is invaded by *Escovopsis* sp, a fungal competitor. In normal conditions, the actinomycete *Pseudonocardia* sp., which grows on the cuticle of all ants of the colony, protects the basidiomycete symbiont against this fungal competitor

5 Economic and Natural Losses

A. octospinosus causes serious damages due to its foraging activity. Calculating the losses resulting from this leaf-cutting ant attack is difficult due to the wide range of damages they cause (Knapp 1987). Damage can represent from 20 to 30 % of the production of some crops and financial losses are enormous in every country where it occurs. The United States Department of Agriculture (USDA) classifies this ant among the most serious pests of tropical and subtropical America (Pollard 1982).

In Trinidad, a study estimated that *Acromyrmex octospinosus* nests could remove 20–25 % of the total leaf area in the first year of a crop of cacao or citrus orchards. This was equivalent to a tree mortality of 6–17 % resulting from defoliation (Lewis 1975; Pollard 1982). In 1968 annual losses due to *A. octospinosus* activities were estimated at US\$250,000 in this country (Pollard 1982).

In Guadeloupe (FWI), *A. octospinosus*, was discovered in 1954 in the vicinity of the Morne-à-l'eau community on the island of Grande Terre (Mikheyev 2008). This species used to be considered only as an agriculture pest. However, a Regional Federation of Defense against Pests (FREDON) survey carried out in 2008 indicated that the ant is present on the whole territory of Guadeloupe. This survey shows that vegetable and fruit crops account for 90.9 % of attacks. The ant has also invaded natural areas in favor of the cyclone of 1995. Constantly expanding, it is found at over 700 m of altitude and is now threatens plant species of protected areas, in particular arborescent ferns of *Cyathea* sp. of rain forest. Some of those may completely disappear due to their endemism.

A. octospinosus is thus classified among the most serious pests of tropical and subtropical America. Due to its foraging activity, it can cause serious damages from 20 to 30 % of crop production. Huge losses were observed in several vegetable and fruit crops, in crop of cacao or citrus orchards and in protected areas (where some species may completely disappear due to their endemism).

6 Pest Management

6.1 Physical Management

The first techniques used to fight against *A. octospinosus* were physical and mechanical methods. They are still in use and consist in flooding, digging, burning, dynamiting or pumping smoke into nests. These methods have only local efficacy and do not prevent from individuals survivors reestablishing the colony (Knapp 1987).

Therefore first techniques used to fight against *A. octospinosus* were mechanical methods, which have only local efficiency and do not prevent from the reestablishment of colonies.

6.2 Synthetic Chemical Management

Chemical control began at the twentieth century and intensified with the Green Revolution. It can be classified into (i) direct application of chemicals and (ii) laying of toxic baits.

Direct chemical control can be applied through liquids, dusts, vapours or thermal fogs. This chemical management was first organized with insecticides and fungicides such as hydrogen cyanide gas, sulfur dioxide, sulfur and arsenic vapors, carbon disulphide or chloropicrin. After 1960, it was fulfilled with synthetic insecticides such as organochlorines: lindane, chlordane, heptachlor, aldrin and dieldrin (Pollard 1982). The efficiency of these products varied. It can disturb the colony or kill some larvae and workers. In most case, survived ants may just abandon the nest and build a new one. Moreover substances used are toxic for humans by contact, ingestion or inhalation and are hazardous for environment. Direct chemical control requires also significant human resources for the work of prospecting and tracking nests.

First uses of toxic baits began in 1963. These baits were made up with agricultural by-products (sugar cane waste, citrus pulp and soybean oil). Their efficiency has been limited and tropical climate induces fermentation and microbial growth in bait (Cherrett 1969). In 1964, began Mirex[®] use whose active insecticidal ingredient was perchlordecone. The active ingredient was released to whole colony by trophallaxis. Attractiveness and efficiency of the baits were ephemeral. In addition, active substance was toxic to humans, highly volatile and hazardous for environment. In 1984, laboratory and *in situ* tests were made with AMDRO (Hydramethylnon), an amidinohydrazone. Baits were made with wheat flour, malting residue or sugarcane residue and soybean oil. This bait missed attractiveness and was weakly efficient on the entire colony. Microencapsulation appeared in 1984. Insecticide was enclosed in a microscopic capsule where active substance was spreading out slowly. Size of microcapsules must be between a few microns and 1 mm in order to be blocked in ant infrabuccal filter (Febvay 1982). This method is less toxic than others pesticides for mammals and birds, but still toxic for bees.

In France (Guadeloupe, FWI), pest management starts in 1956 and until 1963, it consisted in nests exploration and direct application of lindane and heptachlor inside them. From 1963 to 1973, aldrin baits are used until they were forbidden in France. In 1968, Mirex 450[®] (0.45 % perchlordecone) appeared and was intensively used after 1970. It was sold to farmers and common people as granules baits to put at the entrance of nests (Febvay et al. 1990). The perchlordecone is a neurotropic organochlorine that affects sodium channels function needs for the transmission of nervous impulses of insects. This molecule can be degrade to chlordecone and is bioaccumulative, induce insects resistance and is responsible of pollution of soil, water and plants (Cabidoche et al. 2006). Although banned by US Environmental Protection Agency before 1986, Mirex 450[®] was only forbidden in France in 1993. From 1994 to 2003, Department of Plant Protection has authorized the use of Mirex S[®] whose active substance was sulfluramid. The sulfluramid give perfluorooctane sulfonate (PFOS) after degradation. PFOS is a persistant organic pollutant whose adverse effects are very important for human health and environment (UNEP 2007). Since 2003, the active substance authorized by the Ministry of Agriculture and Fisheries for *A. octospinosus* pest management is fipronil at 0.03 g/kg (Blitz[®]). Fipronil (5-amino-3-cyano-1-(2,6-dichloro-4-trifluoromethyl-phenyl)-4-trifluoromethylsulfanylpyrazole), is a phenylpyrazole. Fipronil is a noncompetitive inhibition of GABAergic synapses, alters invertebrate's nerve cells chlorine pumps, inhibits electric control, and induces a hyperexcitability. It is insecticidal by ingestion (Toral 2005).

In 2012, this substance is still used and widely marketed although its environmental toxicity (Official Journal of the French Senate of 17/11/2005, page 2969; UNEP 2007). We have to mention the fact that this substance, as an endocrine disruptor, can also have significant impact on public health (AFSSA 2005).

Thus chemical control against *A. octospinosus* began in the twentieth century with a direct chemical control. It was applied through liquids, dusts, vapours or thermal fogs of hydrogen cyanide gas, sulfur dioxide, sulfur and arsenic vapors, carbon disulphide, chloropicrin or organochlorines. Since 1963, toxic baits (with perchlordecone, hydramethylnon, sulfluramid or fipronil) were successively used. The efficiency of these controls has been limited but all of them were toxic for humans and hazardous for environment.

6.3 Sustainable Pest-Management

First laboratory tests for biological control began in 1939. They consisted in introducing conidial spores of pathogenous fungus into nest. Efficacy of this method was limited because diseases didn't really include in nest and pathogens spores were released by workers. In the same period, field tests consisting in the introduction of ants predators like Acarians, Collembolas and *Phoridae* sp. flies were achieved. The method was not sufficient to reduce ant populations. In 1970, laboratory and field tests were performed with fungal symbiont's extract and trail pheromone

(the compound M4MP2C) (Knapp 1987). *In vitro* efficiency of this test was not being confirmed *in situ*.

Laboratory trials were conducted with entomopathogenic fungus *Entomophthora coronata* (Kermarrec and Mauleon 1975) and the nematodes *Heterorhabditis* sp. and *Neoaplectana* sp. (Kermarrec et al. 1988). These trials did not give the desired effect on *Acromyrmex octospinosus*. In 2007, other tests were performed on other Attines of the genus *Atta* using entomopathogenic fungi *Metarhizium anisopliae*, *Beauveria bassiana* and *Trichoderma viride* (Da Silva and Diehl-Fleig 1988; Lopez and Orduz 2003; Santos et al. 2007). These tests allowed producing a microbiological insecticide: the BIBISAV[®]. Unfortunately, this product did not seem to have the same effect on *A. octospinosus* (Machado et al. 1988). Another study was performed with a different formulation of *Beauveria bassiana* BIBISAV-2[®] which seemed to be capable to reduce activity of *A. octospinosus* (Perez and Trujillo 2002).

Another alternative to chemical control has been explored with the insecticidal activities of plants extracts. Insecticidal activity of two rotenoids (isoflavonoids) extracted from *Lonchocarpus* sp. (Fabaceae) was shown on *Acromyrmex octospinosus* (Petit 2004). *Mammea americana*, *Nerium oleander*, *Nicotiana tabacum*, *Rollinia mucosa* and *Trichillia palida* plant extracts showed various effects on *A. octospinosus* workers (contact toxicity, repellent activity and/or toxicity by ingestion) (Boulogne et al. 2012a).

Other alternative control has been explored on the fungal symbiont. Fungicidal activities of organic extracts of plants were tested. *Allium cepa*, *Allium sativum*, *Lycopersicon esculentum*, *Manihot esculenta* and *Senna alata* plant extracts showed various effects on *Leucocoprinus gongylophorus* *in vitro* cultures (Boulogne et al. 2012b). Results of these tests based on insecticidal and fungicidal plants extracts as an alternative to synthetic chemical control showed very encouraging *in vitro* preliminary results. Indeed natural insecticides and fungicides may serve as alternatives to synthetic compounds to develop safer control agents of leaf-cutting ants.

Hence, since 1939, laboratory and field tests of biological control were performed with introduction of conidial spores of pathogenous fungus or ants predators into nest, with fungal symbiont's extract and trail pheromone, with entomopathogenic fungus and nematodes. The efficiency of most of these methods was limited, did not give the desired effect or were not confirmed *in situ*. Another alternative to chemical control has been explored with the insecticidal or fungicidal activities of plants extracts, which showed various effects on *A. octospinosus* workers (contact toxicity, repellent activity and/or toxicity by ingestion) and various effects on *Leucocoprinus gongylophorus* *in vitro* cultures. These tests showed very encouraging *in vitro* preliminary results and may serve as alternatives to synthetic compounds to develop safer control agents of leaf-cutting ants.

6.4 Integrated Pest-Management

As shown in Fig. 8 (*Pseudonocardia*'s picture is taken from Park et al. 2008), complex relationships between ant, fungus and actinomycete are involved. In this tripartite

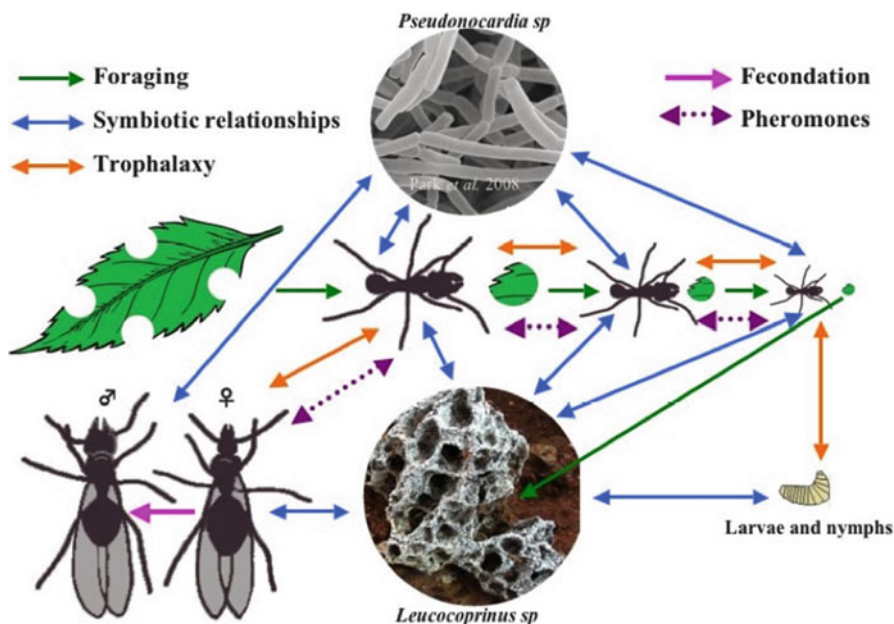


Fig. 8 Complex relationships and tripartite mutualism in nests of the leaf-cutting ant *Acromyrmex octospinosus* between ants, basidiomycete symbiont *Leucocoprinus gongylophorus* and actinomycete symbiont *Pseudonocardia sp.* (*Pseudonocardia*'s picture is taken from Park et al. 2008). Social life of *A. octospinosus* is under pheromones actions (trail, alarm and queen pheromones). Foraging is conditioned by trail pheromone and takes place along a 'line' involving all castes of the colony. There are trophallactic exchanges between larvae and workers and between workers, queen, gynes and males. *Leucocoprinus gongylophorus* is the exclusive nutrition of both the juvenile stages and the queen and is a supplement of adult workers' diet. *Pseudonocardia sp* protects *Leucocoprinus gongylophorus* against this fungal competitor and *A. octospinosus* against entomopathogens

mutualism, fungus serves as primary food source for ants, the actinomycete helps to protect the fungus from specialized parasites and ants take care of the fungus and disperse both fungus and actinomycete to new colonies (Currie 2001). In all studies only one side management was investigated: the insecticidal or the fungicidal level individually.

First we thought that a combination of both strategies should promote a more efficient integrated control. It is the reason why a previous literature review indicated 20 interesting chemicals with both insecticidal and fungicidal activities and 305 plant species containing these chemicals were found (Boulogne et al. 2012c).

Then we hypothesize that, like tripartite mutualism, the management of *A. octospinosus* requires a tripartite management based on a combination of the three strategies.

Consequently we suggest in future studies on the control of *A. octospinosus* that trials focusing on control methods should be conducted for the investigation of

alternatives acting simultaneity on ant, fungus and mutualistic actinomycete. In literature, it has not existing data on effect of alternatives on *Pseudonocardia* sp strains. Early in vitro studies should therefore been conducted on cultures of *Pseudonocardia* by testing substances of plant origin known for their antibacterial and antifungal activities.

Complex relationships and tripartite mutualism are then involved between ants, fungus and actinomycete. All studies investigated only one side management: insecticidal or the fungicidal level individually. A combination of both strategies or a tripartite management based on a combination of the three strategies should promote a more efficient integrated control.

7 Conclusion

Although *Acromyrmex octospinosus* is considered as an important pest, there is a lack of synthesis of information available on it. This fact is probably one of the reasons why there is no effective control of this pest. In addition synthetic chemicals used are not really efficient but hazardous for the environment and human health. Alternative solutions must be quickly found. Several attempts of biological control did not give expected results on *A. octospinosus*. Nevertheless plants extracts gave good results and seemed to have the potential to fight against this insect. Further studies will complete and refine previous works and explore new paths. A combined integrated tripartite pest management (against fungus, insect and actinomycete) with eco-friendly extracts of plant origin could be a solution to explore for efficient and sustainable control of *A. octospinosus*.

Acknowledgements The authors thank CEREGMIA and its director Fred Celimène for financial support to Isabelle Boulogne.

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Impact of Pesticide Productivity on Food Security

József Popp, Károly Pető, and János Nagy

Abstract The seven billion global population is projected to grow by 70 million per annum, increasing by 30 % to 9.2 billion in 2050. This increased population density is projected to increase demand for food production by 70 % notably due to changes in dietary habits in developing countries towards high quality food, e.g. greater consumption of meat and milk products, and to the increasing use of grains for livestock feed. The availability of additional agricultural land is limited. Furthermore, more agricultural land will be used to produce bio-based commodities such as bioenergy or fibre instead of food and feed. Thus, we need to grow food on even less land, with less water, using less energy, fertiliser and pesticide than we use today. Given these limitations, sustainable production at elevated levels is urgently needed. The reduction of current yield losses caused by pests are major challenges to agricultural production. This review presents (1) worldwide crop losses due to pests, (2) estimates of pesticide-related productivity, and costs and benefits of pesticide use, (3) approaches to reduce yield losses by chemical, as well as biological and recombinant methods of pest control, and (4) the challenges of the crop protection industry. However, as long as there is a demand for pesticide-based solutions to pest control problems and food security concerns, the externality problems associated with the human and environmental health effects of pesticides needs also to be addressed.

This chapter is an abridged version of the article Pesticide productivity and food security. A review. *Agronomy for Sustainable Development*: Volume 33, Issue 1 (2013), Page 243–255. DOI [10.1007/s13593-012-0105-x](https://doi.org/10.1007/s13593-012-0105-x). Springer (Popp et al. 2013).

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Keywords Pest control • Pesticide use • Benefits • Externality • Crop protection industry

1 Introduction

The combined effect of the Green Revolution has allowed world food production to double in the past 50 years. From 1960 to present the human population has more than doubled to reach seven billion people. In 2050, the population is projected to increase by 30 % to about 9.2 billion (Fig. 1). Due to increasing global population and changing diets in developing countries towards meat and milk products demand for food production is projected to increase by 70 % (FAO 2009).

Globally, an average of 35 % of potential crop yield is lost to pre-harvest pests (Oerke 2005). In addition to the pre-harvest losses, food chain losses are also relatively high (IWMI 2007). Agriculture has to meet at a global level a rising demand for food, feed, fibre, bioenergy and other bio-based commodities, however, the provision of additional agricultural land is limited. Given these limitations, sustainable production and increasing productivity on existing land is by far the better choice (Fig. 2). Part of the key is also to avoid waste along the whole length of the food chain. Much of the increases in yield per unit of area can be attributed to more efficient control of (biotic) stress rather than an increase in yield potential.

In order to safeguard the high level of food and feed productivity necessary to meet the increasing human demand, these crops require protection from pests (Popp 2011). Helping farmers lose less of their crops will be a key factor in promoting

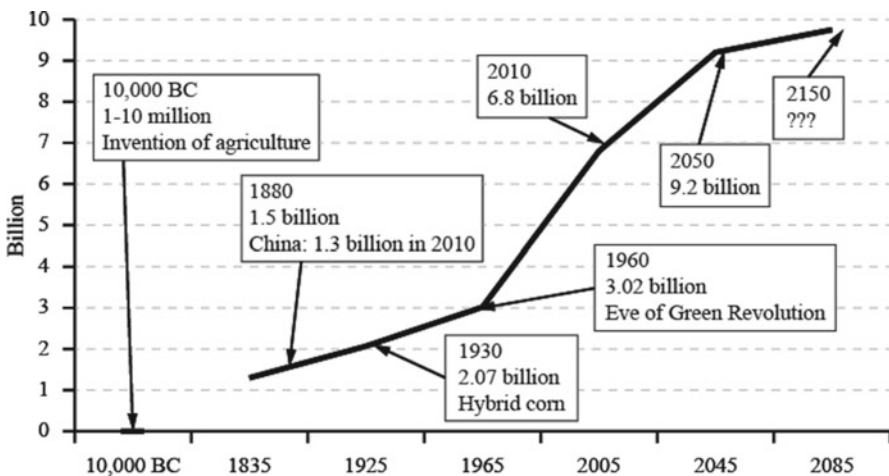


Fig. 1 World population growth. From 1960 to present the human population has more than doubled to reach seven billion people and in 2050, the population is projected to increase by 30 % to about 9.2 billion (Source: FAO 2009)



Fig. 2 Livestock food in the diet. Copyright: FAO/L.Rlung (FAO 2011)

food security. The beneficial outcome from use of pesticides provides evidence that pesticides will continue to be a vital tool in the diverse range of technologies that can maintain and improve living standards for the people of the world (National Research Council 2000).

Globally, agricultural producers apply around USD 40 billion worth of pesticides per annum. The market share of biopesticides is only 2 % of the global crop protection market (McDougall 2010). Farmers in highly developed, industrialised countries expect a four or five fold return on money spent on pesticides (Gianessi and Reigner 2005, 2006; Gianessi 2009). Can we meet world food demands if producers continue, increase or discontinue pesticide use because of reduced economic benefits? This is the greatest challenge facing scientists in history between now and the year 2050 (Popp 2011).

2 Crop Losses to Pests

An average of 35 % of potential crop yield is lost to pre-harvest pests worldwide (Oerke 2005). In addition to the pre-harvest losses transport, pre-processing, storage, processing, packaging, marketing and plate waste losses along the whole food chain account for another 35 % (Fig. 3). In addition to reduce crop losses due to pests avoiding waste along the whole length of the food chain is also key (Popp 2011). Crop protection has been developed for the prevention and control of crop losses due to pests in the field (pre-harvest losses) and during storage (post-harvest losses). This chapter concentrates on pre-harvest losses, i.e. the effect of pests on

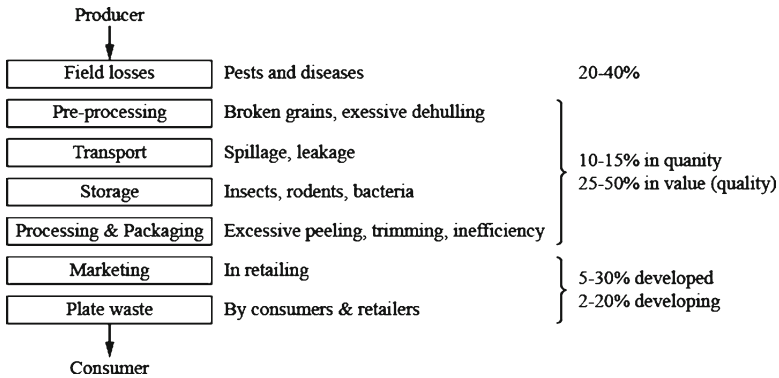


Fig. 3 Losses along the food chain. An average of 35 % of potential crop yield is lost to pre-harvest pests worldwide. In addition to the pre-harvest losses transport, pre-processing, storage, processing, packaging, marketing and plate waste losses along the whole food chain account for another 35 % (Source: IWMI 2007)

crop production in the field, and the effect of control measures applied by farmers in order to minimise losses to an acceptable level (Oerke 2005).

The assessment of crop losses is important for demonstrating where future action is needed and for decision making by farmers as well as at the governmental level. According to German authorities in 1929, animal pests and fungal pathogens each caused a 10 % loss of cereal yield. In potato, pathogens and animal pests reduced production by 25 % and 5 %, respectively; while in sugar beet, production was reduced by 5 % and 10 % due to pathogens and animal pests respectively (Morstatt 1929). In the USA, in the early 1900s pre-harvest losses caused by insect pests were estimated at seldom less than 10 % (Marlatt 1904).

Estimates of actual losses in crop production worldwide were updated for the period 1988–1990 on a regional basis for 17 regions by Oerke et al. (1994). Increased agricultural pesticide use nearly doubled food crop harvests from 42 % of the theoretical worldwide yield in 1965 to 70 % of the theoretical yield by 1990. Unfortunately, 30 % of the theoretical yield was still being lost because the use of effective pest management methods was not applied uniformly around the world and it still is not. Without pesticides 70 % of crop yields could have been lost to pests (Oerke 2005).

Since crop production technology and especially crop protection methods are changing continuously, loss data for eight major food and cash crops – wheat, rice, maize, barley, potatoes, soybeans, sugar beet and cotton – have been updated for the period 1996–1998 on a regional basis for 17 regions (Oerke and Dehne 2004). Among crops the loss potential of pests worldwide varied from less than 50 % (on barley) to more than 80 % (on sugar beet and cotton). Actual losses were estimated at 26–30 % for sugar beet, barley, soybean, wheat and cotton, and 35 %, 39 % and 40 % for maize, potatoes and rice, respectively (Oerke and Dehne 2004).

Table 1 Estimates of actual crop losses due to pests in worldwide production of wheat, maize and cotton

Period	Yield (kg/ha)	Actual loss (%)			Total
		Weeds	Animal pests	Diseases	
<i>Wheat</i>					
1964/1965 ^a	1,250	9.8	5.0	9.1	23.9
1988–1990 ^b	2,409	12.3	9.3	12.4	34.0
1996–1998 ^c	2,610	9.0	8.0	12.0	29.0
2001–2003 ^d	2,691	7.7	7.9	12.6	28.2
<i>Maize</i>					
1964/1965 ^a	2,010	13.0	12.4	9.4	34.8
1988–1990 ^b	3,467	13.1	14.5	10.8	38.3
1996–1998 ^c	4,190	10.0	10.0	10.0	30.0
2001–2003 ^d	4,380	10.5	9.6	11.2	31.2
<i>Cotton</i>					
1964/1965 ^a	1,029	4.5	11.0	9.1	24.6
1988–1990 ^b	1,583	11.8	15.4	10.5	37.7
1996–1998 ^c	1,630	7.0	12.0	10.0	29.0
2001–2003 ^d	1,702	5.6	12.3	7.9	28.8

Source: Cramer (1967), Oerke et al. (1994), Oerke and Dehne (2004), and Oerke (2005) and own calculations

Worldwide estimates for losses to pests in 1996–1998 and 2001–2003 differ significantly from estimates published earlier

^aFrom Cramer (1967)

^bFrom Oerke et al. (1994)

^cFrom Oerke and Dehne (2004)

^dFrom Oerke (2005)

Since the early 1990s, production systems and especially crop protection methods have changed significantly, especially in crops like maize, soybean and cotton, in which the advent of transgenic varieties has modified the strategies for pest control in some major production regions. Loss data for major food and cash crops have been updated most recently by Commonwealth Agricultural Bureaux International's Crop Protection Compendium for six food and cash crops – wheat, rice, maize, potatoes, soybeans, and cotton – for the period 2001–2003 on a regional basis (CABI's Crop Protection Compendium 2005; Oerke 2005). Nineteen regions were specified according to the intensity of crop production and the production conditions. Among crops, the total global potential loss due to pests varied from about 50 % in wheat to more than 80 % in cotton production. The responses are estimated as losses of 26–29 % for soybean, wheat and cotton, and 31 %, 37 % and 40 % for maize, rice and potatoes, respectively.

Worldwide estimates for losses to pests in 1996–1998 and 2001–2003 differ significantly from estimates published earlier (Cramer 1967; Oerke et al. 1994). Obsolete information from old reports has been replaced by new data. Alterations in the share of regions differing in loss rates in total production worldwide are also responsible for differences (Table 1). Moreover, the intensity and efficacy of crop

protection has increased since the late 1980s especially in Asia and Latin America where the use of pesticides increased above the global average (Yudelman et al. 1998). above the global average (Yudelman et al. 1998).

3 Estimates of Pesticide-Related Productivity

The use of pesticides has increased dramatically since the early 1960s; in the same period also the yield average of wheat, rice and maize, the major sources for human nutrition, has more than doubled. Without pesticides, food production would drop and food prices would soar. Where overall crop productivity is low, crop protection is largely limited to some weed control and actual losses to pests may account for more than 50 % of the attainable production (Oerke 2005). Use patterns of pesticides vary with crop type, locality, climate, and user needs. Plant disease can be devastating for crop production, as was tragically illustrated in the Irish potato famine of 1845–1847. This disaster led to the development of the science of plant pathology (Agrios 1988). From the time when synthetic pesticides were developed after World War II, there have been major increases in agricultural productivity accompanied by an increase in efficiency, with fewer farmers on fewer farms producing more food for more people.

Ensuring the safety and quality of foods and the increase in crop loss was accompanied by a growth in the rate of pesticides use. The annual global chemical-pesticide market is about three million tonnes associated with expenditures around USD 40 billion (Popp 2011). The growing dependence on chemical pesticides has been called the “pesticide treadmill” by entomologists (Bosch 1978). A major factor in the “pesticide treadmill” involves two responses to pesticide resistance. The first is to increase the dose and frequency of use of the less effective pesticide; this typically results in higher levels of pest resistance and damage to natural enemies and the environment. The second response is to develop and commercialise a new pesticide. The treadmill concept assumes that this two-step process will continue until the pest meets a resistance-proof pesticide or until the supply of effective new pesticides is exhausted. The greater the impact of control measures on pest populations, the more extreme are their evolutionary responses. However, the moderate rates in yield increase in the major world crops during 1965–2000 did not offer a strong case for a high increase in pesticide use even taking into account the fair amount of change in the cropping systems of developing countries with an expansion of the fruits and vegetable sector (FAO 2000).

Pesticide productivity has been estimated in three general ways: with partial-budget models based on agronomic projections, with combinations of budget and market models, and with econometric models. The most widely cited studies on pesticide productivity, those of Pimentel (Pimentel et al. 1978, 1991, 1992), Cramer (1967) and Knutson et al. (1993) use partial-budget models. One of these studies (Pimentel et al. 1991) estimates that aggregate crop losses amounted to 37 % of total

output in 1986, up from 33 % in 1974. In comparison, Cramer (1967) estimated crop losses of around 28 % due to all pests in all of North and Central America. Estimates of crop losses at 37 % are questionably high. Crop losses of the magnitude estimated by Pimentel et al. (1991) should be sufficient to make it profitable to use chemical pest controls at much greater rates than observed today.

Other studies have attempted to estimate pesticide related effects of large reductions in pesticide use by combining partial-budget models with models of output markets (Zilberman et al. 1991; Ball et al. 1997). These studies use the same approach as partial-budget models in estimating yield and cost effects of changes in pesticide use. The productivity of pesticides – and thus the effects of reducing pesticide use – depends in large measure on substitution possibilities within the agricultural economy (Zilberman et al. 1991). In general, pesticide productivity will tend to be low in situations where substitution possibilities are large. Real prices of energy and durable equipment have fallen relative to agricultural chemical prices (Ball et al. 1997). On the other hand the prices of hired and self-employed labour have risen steadily, both in real terms and relative to agricultural chemical prices, and this suggests that labour-intensive pest-control methods have become less attractive relative to pesticide use. Zilberman et al. (1991) estimated that every dollar increase in pesticide expenditure raises gross agricultural output by USD 3–6. Most of that benefit is passed on to consumers in the form of lower prices for food.

Econometric models capture all forms of substitution in production, including short-term and long-term substitutes for pesticides on individual farms and at the regional and national levels. Headley (1968) estimated such a model by using state-level cross-sectional data in the US for the year 1963. He used crop sales to measure output and expenditures on fertilisers, labour, land and buildings, machinery, pesticides and other inputs as measures of input use and found that an additional dollar spent on pesticides increased the value of output by about USD 4 showing a high level of productivity for that period. The Headley model generates estimates of the marginal productivity associated with pesticides, that is, the additional amount (value) of output obtained by using an additional unit of pesticides. Multiplying the marginal productivity of pesticides by the quantity of pesticides used thus understates the total value added by pesticides (Pimentel et al. 1992). Carrasco-Tauber and Moffitt (1992) applied this approach to state-level cross-sectional data on sales and input expenditures in the U.S. like those used by Headley (1968). Their use of sales as a dependent variable generated an implicit estimate of aggregate US crop losses in 1987 of 7.3 % at average pesticide use, far less than estimates of other studies (Pimentel et al. 1991; Oerke et al. 1994). Chambers and Lichtenberg (1994) developed a dual form of this model based on the assumptions of profit maximisation and separability between normal and damage-control inputs. Implicit crop losses in 1987 estimated from those models ranged from 9 % to 11 %, only about one quarter to one third of the size estimated by others (Pimentel et al. 1991; Oerke et al. 1994). Estimated crop losses with zero pesticide use ranged from 17 to 20 %.