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Sustainable Approaches to Pest-Management: Enhancing Efficacy & Environmental Safety of Pesticides

Mrs.Parveen Saini

Associate Professor in Zoology, Dr.B.R.Ambedkar College, Sri Ganganagar, Rajasthan, India

ABSTRACT: Integrated pest management (IPM), also known as integrated pest control (IPC) or sustainable management is a broad-based approach that integrates both chemical and non-chemical practices for economic control of pests. IPM aims to suppress pest populations below the economic injury level (EIL). The UN's Food and Agriculture Organization defines IPM as "the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment. IPM emphasizes the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms."[1] Entomologists and ecologists have urged the adoption of IPM pest control since the 1970s.[2] IPM allows for safer pest control.

The introduction and spread of invasive species can also be managed with IPM by reducing risks while maximizing benefits and reducing costs.[3][4][5]

KEYWORDS: Sustainable,Integrated,Pest,Management,Control,Populations,Ecology,Cost

I.INTRODUCTION

Shortly after World War II, when synthetic insecticides became widely available, entomologists in California developed the concept of "supervised insect control".[6] Around the same time, entomologists in the US Cotton Belt were advocating a similar approach. Under this scheme, insect control was "supervised" by qualified entomologists and insecticide applications were based on conclusions reached from periodic monitoring of pest and natural-enemy populations. This was viewed as an alternative to calendar-based programs. Supervised control was based on knowledge of the ecology and analysis of projected trends in pest and natural-enemy populations.

Supervised control formed much of the conceptual basis for the "integrated control" that University of California entomologists articulated in the 1950s. Integrated control sought to identify the best mix of chemical and biological controls for a given insect pest. Chemical insecticides were to be used in the manner least disruptive to biological control. The term "integrated" was thus synonymous with "compatible." Chemical controls were to be applied only after regular monitoring indicated that a pest population had reached a level that required treatment (the economic threshold) to prevent the population from reaching a level at which economic losses would exceed the cost of the control measures (the economic injury level).

IPM extended the concept of integrated control to all classes of pests and was expanded to include all tactics. Controls such as pesticides were to be applied as in integrated control, but these now had to be compatible with tactics for all classes of pests. Other tactics, such as host-plant resistance and cultural manipulations, became part of the IPM framework. IPM combined entomologists, plant pathologists, nematologists and weed scientists.

In the United States, IPM was formulated into national policy in February 1972 when President Richard Nixon directed federal agencies to take steps to advance the application of IPM in all relevant sectors. In 1979, President Jimmy Carter established an interagency IPM Coordinating Committee to ensure development and implementation of IPM practices.[7]

Perry Adkisson and Ray F. Smith received the 1997 World Food Prize for encouraging the use of IPM.[8]

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Applications

IPM is used in agriculture, horticulture, forestry, human habitations, preventive conservation of cultural property and general pest control, including structural pest management, turf pest management and ornamental pest management. IPM practices help to prevent and slow the development of resistance, known as resistance management.[9][10][11]

Principles

An American IPM system is designed around six basic components:[12]

- Acceptable pest levels—The emphasis is on *control*, not *eradication*. IPM holds that wiping out an entire pest population is often impossible, and the attempt can be expensive and unsafe. IPM programmes first work to establish acceptable pest levels, called action thresholds, and apply controls if those thresholds are crossed. These thresholds are pest and site specific, meaning that it may be acceptable at one site to have a weed such as white clover, but not at another site. Allowing a pest population to survive at a reasonable threshold reduces selection pressure. This lowers the rate at which a pest develops resistance to a control, because if almost all pests are killed then those that have resistance will provide the genetic basis of the future population. Retaining a significant number of unresistant specimens dilutes the prevalence of any resistant genes that appear. Similarly, the repeated use of a single class of controls will create pest populations that are more resistant to that class, whereas alternating among classes helps prevent this.[13]
- Preventive cultural practices—Selecting varieties best for local growing conditions and maintaining healthy crops is the first line of defense. Plant quarantine and 'cultural techniques' such as crop sanitation are next, e.g., removal of diseased plants, and cleaning pruning shears to prevent spread of infections. Beneficial fungi and bacteria are added to the potting media of horticultural crops vulnerable to root diseases, greatly reducing the need for fungicides.
- Monitoring—Regular observation is critically important. Observation is broken into inspection and identification.[14] Visual inspection, insect and spore traps, and other methods are used to monitor pest levels. Record-keeping is essential, as is a thorough knowledge of target pest behavior and reproductive cycles. Since insects are cold-blooded, their physical development is dependent on area temperatures. Many insects have had their development cycles modeled in terms of degree-days. The degree days of an environment determines the optimal time for a specific insect outbreak. Plant pathogens follow similar patterns of response to weather and season.
- Mechanical controls—Should a pest reach an unacceptable level, mechanical methods are the first options. They include simple hand-picking, barriers, traps, vacuuming and tillage to disrupt breeding.
- Biological controls—Natural biological processes and materials can provide control, with acceptable environmental impact, and often at lower cost. The main approach is to promote beneficial insects that eat or parasitize target pests. Biological insecticides, derived from naturally occurring microorganisms (*e.g.*—*Bt*, entomopathogenic fungi and entomopathogenic nematodes), also fall in this category. Further 'biology-based' or 'ecological' techniques are under evaluation.
- Responsible use—Synthetic pesticides are used as required and often only at specific times in a pest's life cycle. Many newer pesticides are derived from plants or naturally occurring substances (*e.g.*—nicotine, pyrethrum and insect juvenile hormone analogues), but the toxophore or active component may be altered to provide increased biological activity or stability. Applications of pesticides must reach their intended targets. Matching the application technique to the crop, the pest, and the pesticide is critical. The use of low-volume spray equipment reduces overall pesticide use and labor cost.

An IPM regime can be simple or sophisticated. Historically, the main focus of IPM programmes was on agricultural insect pests.[15] Although originally developed for agricultural pest management, IPM programmes are now developed to encompass diseases, weeds and other pests that interfere with management objectives for sites such as residential and commercial structures, lawn and turf areas, and home and community gardens. Predictive models have proved to be suitable tools supporting the implementation of IPM programmes.[16]

II.DISCUSSION

IPM is the selection and [16] use of pest control actions that will ensure favourable economic condition, ecological and social consequences[17] and is applicable to most agricultural, public health and amenity pest management situations. The IPM process starts with monitoring, which includes inspection and identification, followed by the establishment of

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economic injury levels. The economic injury levels set the economic threshold level. That is the point when pest damage (and the benefits of treating the pest) exceed the cost of treatment.[18] This can also be an action threshold level for determining an unacceptable level that is not tied to economic injury. Action thresholds are more common in structural pest management and economic injury levels in classic agricultural pest management. An example of an action threshold is one fly in a hospital operating room is not acceptable, but one fly in a pet kennel would be acceptable. Once a threshold has been crossed by the pest population action steps need to be taken to reduce and control the pest. Integrated pest management employs a variety of actions including cultural controls such as physical barriers, biological controls such as adding and conserving natural predators and enemies of the pest, and finally chemical controls or pesticides. Reliance on knowledge, experience, observation and integration of multiple techniques makes IPM appropriate for organic farming (excluding synthetic pesticides). These may or may not include materials listed on the Organic Materials Review Institute (OMRI)[19] Although the pesticides and particularly insecticides used in organic farming and organic gardening are generally safer than synthetic pesticides, they are not always more safe or environmentally friendly than synthetic pesticides and can cause harm.[20] For conventional farms IPM can reduce human and environmental exposure to hazardous chemicals, and potentially lower overall costs.[

Risk assessment usually includes four issues: 1) characterization of biological control agents, 2) health risks, 3) environmental risks and 4) efficacy.[21]

Mistaken identification of a pest may result in ineffective actions. E.g., plant damage due to over-watering could be mistaken for fungal infection, since many fungal and viral infections arise under moist conditions.

Monitoring begins immediately, before the pest's activity becomes significant. Monitoring of agricultural pests includes tracking soil/planting media fertility and water quality. Overall plant health and resistance to pests is greatly influenced by pH, alkalinity, of dissolved mineral and oxygen reduction potential. Many diseases are waterborne, spread directly by irrigation water and indirectly by splashing.

Once the pest is known, knowledge of its lifecycle provides the optimal intervention points.[22] For example, weeds reproducing from last year's seed can be prevented with mulches and pre-emergent herbicide. Pest-tolerant crops such as soybeans may not warrant interventions unless the pests are numerous or rapidly increasing. Intervention is warranted if the expected cost of damage by the pest is more than the cost of control. Health hazards may require intervention that is not warranted by economic considerations.

Specific sites may also have varying requirements. E.g., white clover may be acceptable on the sides of a tee box on a golf course, but unacceptable in the fairway where it could confuse the field of play.[23]

Possible interventions include mechanical/physical, cultural, biological and chemical. Mechanical/physical controls include picking pests off plants, or using netting or other material to exclude pests such as birds from grapes or rodents from structures. Cultural controls include keeping an area free of conducive conditions by removing waste or diseased plants, flooding, sanding, and the use of disease-resistant crop varieties.[17] Biological controls are numerous. They include: conservation of natural predators or augmentation of natural predators, sterile insect technique (SIT).[24]

Augmentation, inoculative release and inundative release are different methods of biological control that affect the target pest in different ways. Augmentative control includes the periodic introduction of predators.[25][26][27][28][29] With inundative release, predators are collected, mass-reared and periodically released in large numbers into the pest area.[30][31][32] This is used for an immediate reduction in host populations, generally for annual crops, but is not suitable for long run use.[33] With inoculative release a limited number of beneficial organisms are introduced at the start of the growing season. This strategy offers long term control as the organism's progeny affect pest populations throughout the season and is common in orchards.[33][34] With seasonal inoculative release the beneficials are collected, mass-reared and released seasonally to maintain the beneficial population. This is commonly used in greenhouses.[34] In America and other western countries, inundative releases are predominant, while Asia and the eastern Europe more commonly use inoculation and occasional introductions.[33]

The sterile insect technique (SIT) is an area-wide IPM program that introduces sterile male pests into the pest population to trick females into (unsuccessful) breeding encounters, providing a form of birth control and reducing reproduction rates.[24] The biological controls mentioned above only appropriate in extreme cases, because in the introduction of new species, or supplementation of naturally occurring species can have detrimental ecosystem effects. Biological controls can be used to stop invasive species or pests, but they can become an introduction path for new pests.[35]

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Chemical controls include horticultural oils or the application of insecticides and herbicides. A green pest management IPM program uses pesticides derived from plants, such as botanicals, or other naturally occurring materials.

Pesticides can be classified by their modes of action. Rotating among materials with different modes of action minimizes pest resistance.[17]

Evaluation is the process of assessing whether the intervention was effective, whether it produced unacceptable side effects, whether to continue, revise or abandon the program.[36]

Southeast Asia

The Green Revolution of the 1960s and '70s introduced sturdier plants that could support the heavier grain loads resulting from intensive fertilizer use. Pesticide imports by 11 Southeast Asian countries grew nearly sevenfold in value between 1990 and 2010, according to FAO statistics, with disastrous results. Rice farmers become accustomed to spraying soon after planting, triggered by signs of the leaf folder moth, which appears early in the growing season. It causes only superficial damage and doesn't reduce yields. In 1986, Indonesia banned 57 pesticides and completely stopped subsidizing their use. Progress was reversed in the 2000s, when growing production capacity, particularly in China, reduced prices. Rice production in Asia more than doubled. But it left farmers believing more is better—whether it's seed, fertilizer, or pesticides.[37]

The brown planthopper, *Nilaparvata lugens*, the farmers' main target, has become increasingly resistant. Since 2008, outbreaks have devastated rice harvests throughout Asia, but not in the Mekong Delta. Reduced spraying allowed natural predators to neutralize planthoppers in Vietnam. In 2010 and 2011, massive planthopper outbreaks hit 400,000 hectares of Thai rice fields, causing losses of about $64 million. The Thai government is now pushing the "no spray in the first 40 days" approach.[37]

By contrast early spraying kills frogs, spiders, wasps and dragonflies that prey on the later-arriving and dangerous planthopper and produced resistant strains. Planthoppers now require pesticide doses 500 times greater than originally. Overuse indiscriminately kills beneficial insects and decimates bird and amphibian populations. Pesticides are suspected of harming human health and became a common means for rural Asians to commit suicide.[37]

In 2001, scientists challenged 950 Vietnamese farmers to try IPM. In one plot, each farmer grew rice using their usual amounts of seed and fertilizer, applying pesticide as they chose. In a nearby plot, less seed and fertilizer were used and no pesticides were applied for 40 days after planting. Yields from the experimental plots was as good or better and costs were lower, generating 8% to 10% more net income. The experiment led to the "three reductions, three gains" campaign, claiming that cutting the use of seed, fertilizer and pesticide would boost yield, quality and income. Posters, leaflets, TV commercials and a 2004 radio soap opera that featured a rice farmer who gradually accepted the changes. It didn't hurt that a 2006 planthopper outbreak hit farmers using insecticides harder than those who didn't. Mekong Delta farmers cut insecticide spraying from five times per crop cycle to zero to one. The Plant Protection Center and the International Rice Research Institute (IRRI) have been encouraging farmers to grow flowers, okra and beans on rice paddy banks, instead of stripping vegetation, as was typical. The plants attract bees and a tiny wasp that eats planthopper eggs, while the vegetables diversify farm incomes.[37]

Agriculture companies offer bundles of pesticides with seeds and fertilizer, with incentives for volume purchases. A proposed law in Vietnam requires licensing pesticide dealers and government approval of advertisements to prevent exaggerated claims. Insecticides that target other pests, such as *Scirpophaga incertulas* (stem borer), the larvae of moth species that feed on rice plants allegedly yield gains of 21% with proper use.[37]

III.RESULTS

The International Organization for Biological and Integrated Control (IOBC), is an organization, affiliated with the International Union of Biological Sciences (IUBS), organised to promote and study biological pest control, integrated pest management (IPM) and integrated production. The IOBC serves as a resource for international organizations, for example: the European Commission on sustainable use of pesticides[1] and the status of IPM in Europe,[2] the EC Regulation of Biological Control Agents with regard to invertebrate biological control agents,[3] the Consultative Group on International Agricultural Research on IPM,[4] the European and Mediterranean Plant Protection Organization on biological control agents[5] and the Food and Agriculture Organization with respect to the Convention on Biological Diversity.[6][7]

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History and structure

A complete history of the IOBC was published in 1988.[8] Briefly, in 1948, the idea of an international organization on biological control was conceived. By 1950, the IUBS decided to support the establishment of a "Commission Internationale de Lutte Biologique" (CILB) as part of the IUBS Division of Animal Biology and a committee was established to further this concept. In 1955, the statutes of the new organization were ratified by the IUBS and the first plenary session of the CILB took place at Antibes, France. In 1965, CILB changed its name from "Commission" to "Organization" thus becoming the "International Organization of Biological Control of Noxious Animals and Plants". In 1969, under the auspices of the IUBS, an agreement was reached among organizations to merge IOBC and the "International advisory committee for biological Control" (active in English-speaking countries) into a single international organization under the name IOBC. The scientific journal *Entomophaga* was the official journal of the organization, until superseded by *BioControl*. In 1971, Global IOBC was established and the former IOBC became the West Palearctic Regional Section.

There are six regional sections world-wide:

- Afrotropical[9]
- Asia and Pacific[10]
- East Palearctic[11]
- Nearctic[12]
- Neotropical[13]
- West Palearctic[14]

Goals and purpose

The IOBC promotes the development of biological control and its application in integrated pest management and international cooperation to these ends.

The IOBC collects, evaluates and disseminates information about biological control and promotes national and international action concerning research, training of personnel, coordination of large-scale application and public awareness of the economic and social importance of biological control.

The IOBC arranges conferences, meetings and symposia, and takes other actions to implement its general objectives.

Global IOBC

In addition to serving as an umbrella organization for the six regional sections, the global organization publishes proceedings of meetings, a newsletter, books, and has 10 working groups. These groups meet to discuss specific topics, usually agricultural pests which may often have a global impact.

Quality Control Standards

A set of standards were developed for assessing the quality control of commercially produced biological control agents.[15][16] These guidelines have been used.[17][18][19][20][21]

Commission on Biological Control and Access and Benefit Sharing

Under the 1993 Convention on Biological Diversity, countries have sovereign rights over their genetic resources, such as species collected for potential use in biological control. This convention was put in place because the profits from prospecting biodiversity have disproportionately benefited corporations from developed countries. Because researchers and Western businesses complained that giving developing countries such rights is problematic due to the new difficulties in legally acquiring potentially profitable species in several countries,[22] the Commission on Biological Control and Access and Benefit Sharing was established in 2008 to allow such parties access to these resources, with the supposition that any benefits arising from such access should be shared.[23] Parties continue to complain they need more access to the genetic resources of other countries than these standards allow.[24]

West Palaearctic Regional Section

The West Palaearctic Regional Section (i.e. Europe) is the most active of the regional sections with 20 working groups (that focus on crops, agricultural pests, and other topics) and five commissions which usually meet in different

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locations in member countries. It produces the *IOBC/WPRS Bulletin*, which in 2007 was listed as one of the top research journals for the organic industry.[25]

Pesticide side-effects standards

The "Pesticides and Beneficial Organisms working group" is made up of scientists from many countries. They establish standards, which are periodically updated, for testing the side effects of pesticides on a large range of natural enemies of crop pests, and rank those effects.[26][27][28][29] The purpose of establishing these standards is to be able to compare pesticides by their effect on beneficial organisms throughout all regions of the world. With the results obtained from these standardized tests, the best pesticides can be identified which enable enhanced survival of non-target organisms and the most biological control due to reduced impact on beneficial organisms.[30] These standards have been adopted a number of scientists worldwide.[31][32][33][34]

Integrated Production

One of the working groups is on Integrated Pest Management and Integrated Production,[35] a concept of agriculture based on the sustainable use of natural resources.[36][37] This group has established crop specific guidelines for pome fruits, stone fruits, grapes, soft fruits, olives, citrus and field grown vegetables in Europe.[38][39]

IMPLICATIONS

Biological control or biocontrol is a method of controlling pests, whether pest animals such as insects and mites, weeds, or pathogens affecting animals or plants by using other organisms.[1] It relies on predation, parasitism, herbivory, or other natural mechanisms, but typically also involves an active human management role. It can be an important component of integrated pest management (IPM) programs.

There are three basic strategies for biological control: classical (importation), where a natural enemy of a pest is introduced in the hope of achieving control; inductive (augmentation), in which a large population of natural enemies are administered for quick pest control; and inoculative (conservation), in which measures are taken to maintain natural enemies through regular reestablishment.[2]

Natural enemies of insects play an important part in limiting the densities of potential pests. Biological control agents such as these include predators, parasitoids, pathogens, and competitors. Biological control agents of plant diseases are most often referred to as antagonists. Biological control agents of weeds include seed predators, herbivores, and plant pathogens.

Biological control can have side-effects on biodiversity through attacks on non-target species by any of the above mechanisms, especially when a species is introduced without a thorough understanding of the possible consequences.

History

The term "biological control" was first used by Harry Scott Smith at the 1919 meeting of the Pacific Slope Branch of the American Association of Economic Entomologists, in Riverside, California.[3] It was brought into more widespread use by the entomologist Paul H. DeBach (1914–1993) who worked on citrus crop pests throughout his life.[4][5] However, the practice has previously been used for centuries. The first report of the use of an insect species to control an insect pest comes from "Nanfang Caomu Zhuang" (南方草木狀 *Plants of the Southern Regions*) (c. 304 AD), attributed to Western Jin dynasty botanist *Ji Han* (嵇含, 263–307), in which it is mentioned that "*Jiaozhi people sell ants and their nests attached to twigs looking like thin cotton envelopes, the reddish-yellow ant being larger than normal. Without such ants, southern citrus fruits will be severely insect-damaged*".[6] The ants used are known as *huang gan* (*huang* = yellow, *gan* = citrus) ants (*Oecophylla smaragdina*). The practice was later reported by Ling Biao Lu Yi (late Tang Dynasty or Early Five Dynasties), in *Ji Le Pian* by *Zhuang Jisu* (Southern Song Dynasty), in the *Book of Tree Planting* by Yu Zhen Mu (Ming Dynasty), in the book *Guangdong Xing Yu* (17th century), *Lingnan* by Wu Zhen Fang (Qing Dynasty), in *Nanyue Miscellanies* by Li Diao Yuan, and others.[6]

Biological control techniques as we know them today started to emerge in the 1870s. During this decade, in the US, the Missouri State Entomologist C. V. Riley and the Illinois State Entomologist W. LeBaron began within-state redistribution of parasitoids to control crop pests. The first international shipment of an insect as a biological control agent was made by Charles V. Riley in 1873, shipping to France the predatory mites *Tyroglyphus phylloxera* to help fight the grapevine phylloxera (*Daktulosphaira vitifoliae*) that was destroying grapevines in France. The United States Department of Agriculture (USDA) initiated research in classical biological control following the establishment of the

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Division of Entomology in 1881, with C. V. Riley as Chief. The first importation of a parasitoidal wasp into the United States was that of the braconid *Cotesia glomerata* in 1883–1884, imported from Europe to control the invasive cabbage white butterfly, *Pieris rapae*. In 1888–1889 the vedalia beetle, *Novius cardinalis*, a lady beetle, was introduced from Australia to California to control the cottony cushion scale, *Icerya purchasi*. This had become a major problem for the newly developed citrus industry in California, but by the end of 1889, the cottony cushion scale population had already declined. This great success led to further introductions of beneficial insects into the US.[7][8]

In 1905 the USDA initiated its first large-scale biological control program, sending entomologists to Europe and Japan to look for natural enemies of the spongy moth, *Lymantria dispar dispar*, and the brown-tail moth, *Euproctis chrysorrhoea*, invasive pests of trees and shrubs. As a result, nine parasitoids (solitary wasps) of the spongy moth, seven of the brown-tail moth, and two predators of both moths became established in the US. Although the spongy moth was not fully controlled by these natural enemies, the frequency, duration, and severity of its outbreaks were reduced and the program was regarded as successful. This program also led to the development of many concepts, principles, and procedures for the implementation of biological control programs.[7][8][9]

Cactoblastis cactorum larvae feeding on *Opuntia* prickly pear cacti

Prickly pear cacti were introduced into Queensland, Australia as ornamental plants, starting in 1788. They quickly spread to cover over 25 million hectares of Australia by 1920, increasing by 1 million hectares per year. Digging, burning, and crushing all proved ineffective. Two control agents were introduced to help control the spread of the plant, the cactus moth *Cactoblastis cactorum*, and the scale insect *Dactylopius*. Between 1926 and 1931, tens of millions of cactus moth eggs were distributed around Queensland with great success, and by 1932, most areas of prickly pear had been destroyed.[10]

The first reported case of a classical biological control attempt in Canada involves the parasitoidal wasp *Trichogramma minutum*. Individuals were caught in New York State and released in Ontario gardens in 1882 by William Saunders, a trained chemist and first Director of the Dominion Experimental Farms, for controlling the invasive currantworm *Nematus ribesii*. Between 1884 and 1908, the first Dominion Entomologist, James Fletcher, continued introductions of other parasitoids and pathogens for the control of pests in Canada.[11]

Types of biological pest control

There are three basic biological pest control strategies: importation (classical biological control), augmentation and conservation.[12]

Importation

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Rodolia cardinalis, the vedalia beetle, was imported from Australia to California in the 19th century, successfully controlling cottony cushion scale.

Importation or classical biological control involves the introduction of a pest's natural enemies to a new locale where they do not occur naturally. Early instances were often unofficial and not based on research, and some introduced species became serious pests themselves.[13]

To be most effective at controlling a pest, a biological control agent requires a colonizing ability which allows it to keep pace with changes to the habitat in space and time. Control is greatest if the agent has temporal persistence so that it can maintain its population even in the temporary absence of the target species, and if it is an opportunistic forager, enabling it to rapidly exploit a pest population.[14]

One of the earliest successes was in controlling *Icerya purchasi* (cottony cushion scale) in Australia, using a predatory insect *Rodolia cardinalis* (the vedalia beetle). This success was repeated in California using the beetle and a parasitoidal fly, *Cryptochaetum iceryae*.[15] Other successful cases include the control of *Antonina graminis* in Texas by *Neodusmetia sangwani* in the 1960s.[16]

Damage from *Hypera postica*, the alfalfa weevil, a serious introduced pest of forage, was substantially reduced by the introduction of natural enemies. 20 years after their introduction the population of weevils in the alfalfa area treated for alfalfa weevil in the Northeastern United States remained 75 percent down.[17]

The invasive species *Alternanthera philoxeroides* (alligator weed) was controlled in Florida (U.S.) by introducing alligator weed flea beetle.

Alligator weed was introduced to the United States from South America. It takes root in shallow water, interfering with navigation, irrigation, and flood control. The alligator weed flea beetle and two other biological controls were released in Florida, greatly reducing the amount of land covered by the plant.[18] Another aquatic weed, the giant salvinia (*Salvinia molesta*) is a serious pest, covering waterways, reducing water flow and harming native species. Control with the salvinia weevil (*Cyrtobagous salviniae*) and the salvinia stem-borer moth (*Samea multiplicalis)* is effective in warm climates,[19][20] and in Zimbabwe, a 99% control of the weed was obtained over a two-year period.[21]

Small commercially reared parasitoidal wasps,[12] *Trichogramma ostriniae*, provide limited and erratic control of the European corn borer (*Ostrinia nubilalis*), a serious pest. Careful formulations of the bacterium *Bacillus thuringiensis* are more effective. The O. nubilalis integrated control releasing *Tricogramma brassicae* (egg parasitoid) and later *Bacillus thuringiensis subs. kurstaki* (larvicide effect) reduce pest damages as better than insecticide treatments [22]

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The population of *Levuana iridescens*, the Levuana moth, a serious coconut pest in Fiji, was brought under control by a classical biological control program in the 1920s.[23]

Augmentation

Hippodamia convergens, the convergent lady beetle, is commonly sold for biological control of aphids.

Augmentation involves the supplemental release of natural enemies that occur in a particular area, boosting the naturally occurring populations there. In inoculative release, small numbers of the control agents are released at intervals to allow them to reproduce, in the hope of setting up longer-term control and thus keeping the pest down to a low level, constituting prevention rather than cure. In inundative release, in contrast, large numbers are released in the hope of rapidly reducing a damaging pest population, correcting a problem that has already arisen. Augmentation can be effective, but is not guaranteed to work, and depends on the precise details of the interactions between each pest and control agent.[24]

An example of inoculative release occurs in the horticultural production of several crops in greenhouses. Periodic releases of the parasitoidal wasp, *Encarsia formosa*, are used to control greenhouse whitefly,[25] while the predatory mite *Phytoseiulus persimilis* is used for control of the two-spotted spider mite.[26]

The egg parasite *Trichogramma* is frequently released inundatively to control harmful moths. New way for inundative releases are now introduced i.e. use of drones. Egg parasitoids are able to find the eggs of the target host by means of several cues. Kairomones were found on moth scales. Similarly, *Bacillus thuringiensis* and other microbial insecticides are used in large enough quantities for a rapid effect.[24] Recommended release rates for *Trichogramma* in vegetable or field crops range from 5,000 to 200,000 per acre (1 to 50 per square metre) per week according to the level of pest infestation.[27] Similarly, nematodes that kill insects (that are entomopathogenic) are released at rates of millions and even billions per acre for control of certain soil-dwelling insect pests.[28]

Conservation

The conservation of existing natural enemies in an environment is the third method of biological pest control.[29] Natural enemies are already adapted to the habitat and to the target pest, and their conservation can be simple and cost-effective, as when nectar-producing crop plants are grown in the borders of rice fields. These provide nectar to support parasitoids and predators of planthopper pests and have been demonstrated to be so effective (reducing pest densities by 10- or even 100-fold) that farmers sprayed 70% less insecticides and enjoyed yields boosted by 5%.[30] Predators of aphids were similarly found to be present in tussock grasses by field boundary hedges in England, but they spread too slowly to reach the centers of fields. Control was improved by planting a meter-wide strip of tussock grasses in field centers, enabling aphid predators to overwinter there.[29]

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An inverted flowerpot filled with straw to attract earwigs

Cropping systems can be modified to favor natural enemies, a practice sometimes referred to as habitat manipulation. Providing a suitable habitat, such as a shelterbelt, hedgerow, or beetle bank where beneficial insects such as parasitoidal wasps can live and reproduce, can help ensure the survival of populations of natural enemies. Things as simple as leaving a layer of fallen leaves or mulch in place provides a suitable food source for worms and provides a shelter for insects, in turn being a food source for such beneficial mammals as hedgehogs and shrews. Compost piles and stacks of wood can provide shelter for invertebrates and small mammals. Long grass and ponds support amphibians. Not removing dead annuals and non-hardy plants in the autumn allow insects to make use of their hollow stems during winter.[31] In California, prune trees are sometimes planted in grape vineyards to provide an improved overwintering habitat or refuge for a key grape pest parasitoid.[32] The providing of artificial shelters in the form of wooden caskets, boxes or flowerpots is also sometimes undertaken, particularly in gardens, to make a cropped area more attractive to natural enemies. For example, earwigs are natural predators that can be encouraged in gardens by hanging upside-down flowerpots filled with straw or wood wool. Green lacewings can be encouraged by using plastic bottles with an open bottom and a roll of cardboard inside. Birdhouses enable insectivorous birds to nest; the most useful birds can be attracted by choosing an opening just large enough for the desired species.[31]

In cotton production, the replacement of broad-spectrum insecticides with selective control measures such as Bt cotton can create a more favorable environment for natural enemies of cotton pests due to reduced insecticide exposure risk. Such predators or parasitoids can control pests not affected by the Bt protein. Reduced prey quality and abundance associated with increased control from Bt cotton can also indirectly decrease natural enemy populations in some cases, but the percentage of pests eaten or parasitized in Bt and non-Bt cotton are often similar.[33]

Biological control agents

Predators

Predatory lacewings are available from biocontrol dealers.

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Predators are mainly free-living species that directly consume a large number of prey during their whole lifetime. Given that many major crop pests are insects, many of the predators used in biological control are insectivorous species. Lady beetles, and in particular their larvae which are active between May and July in the northern hemisphere, are voracious predators of aphids, and also consume mites, scale insects and small caterpillars. The spotted lady beetle (*Coleomegilla maculata*) is also able to feed on the eggs and larvae of the Colorado potato beetle (*Leptinotarsa decemlineata*).[34]

The larvae of many hoverfly species principally feed upon aphids, one larva devouring up to 400 in its lifetime. Their effectiveness in commercial crops has not been studied.[35]

The running crab spider *Philodromus cespitum* also prey heavily on aphids, and act as a biological control agent in European fruit orchards.[36]

Predatory *Polistes* wasp searching for bollworms or other caterpillars on a cotton plant

Several species of entomopathogenic nematode are important predators of insect and other invertebrate pests.[37][38] Entomopathogenic nematodes form a stress–resistant stage known as the infective juvenile. These spread in the soil and infect suitable insect hosts. Upon entering the insect they move to the hemolymph where they recover from their stagnated state of development and release their bacterial symbionts. The bacterial symbionts reproduce and release toxins, which then kill the host insect.[38][39] *Phasmarhabditis hermaphrodita* is a microscopic nematode that kills slugs. Its complex life cycle includes a free-living, infective stage in the soil where it becomes associated with a pathogenic bacteria such as *Moraxella osloensis*. The nematode enters the slug through the posterior mantle region, thereafter feeding and reproducing inside, but it is the bacteria that kill the slug. The nematode is available commercially in Europe and is applied by watering onto moist soil.[40] Entomopathogenic nematodes have a limited shelf life because of their limited resistance to high temperature and dry conditions.[39] The type of soil they are applied to may also limit their effectiveness.[38]

Species used to control spider mites include the predatory mites *Phytoseiulus persimilis*,[41] *Neoseilus californicus,*[42] and *Amblyseius cucumeris*, the predatory midge *Feltiella acarisuga*,[42] and a ladybird *Stethorus punctillum*.[42] The bug *Orius insidiosus* has been successfully used against the two-spotted spider mite and the western flower thrips (*Frankliniella occidentalis*).[43]

Predators including *Cactoblastis cactorum* (mentioned above) can also be used to destroy invasive plant species. As another example, the poison hemlock moth (*Agonopterix alstroemeriana)* can be used to control poison hemlock (*Conium maculatum*). During its larval stage, the moth strictly consumes its host plant, poison hemlock, and can exist at hundreds of larvae per individual host plant, destroying large swathes of the hemlock.[44]

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The parasitoid wasp *Aleiodes indiscretus* parasitizing a spongy moth caterpillar, a serious pest of forestry[45]

For rodent pests, cats are effective biological control when used in conjunction with reduction of "harborage"/hiding locations.[46][47][48] While cats are effective at preventing rodent "population explosions", they are not effective for eliminating pre-existing severe infestations.[48] Barn owls are also sometimes used as biological rodent control.[49] Although there are no quantitative studies of the effectiveness of barn owls for this purpose,[50] they are known rodent predators that can be used in addition to or instead of cats;[51][52] they can be encouraged into an area with nest boxes.[53][54]

In Honduras, where the mosquito *Aedes aegypti* was transmitting dengue fever and other infectious diseases, biological control was attempted by a community action plan; copepods, baby turtles, and juvenile tilapia were added to the wells and tanks where the mosquito breeds and the mosquito larvae were eliminated.[55]

Even amongst arthropods usually thought of as obligate predators of animals (especially other arthropods), floral food sources (nectar and to a lesser degree pollen) are often useful adjunct sources.[56] It had been noticed in one study[57] that adult *Adalia bipunctata* (predator and common biocontrol of *Ephestia kuehniella*) could survive on flowers but never completed its life cycle, so a meta-analysis[56] was done to find such an overall trend in previously published data, if it existed. In some cases floral resources are outright necessary.[56] Overall, floral resources (and an imitation, i.e. sugar water) increase longevity and fecundity, meaning even predatory population numbers can depend on non-prey food abundance.[56] Thus biocontrol population maintenance - and success - may depend on nearby flowers.[56]

Parasitoids

Parasitoids lay their eggs on or in the body of an insect host, which is then used as a food for developing larvae. The host is ultimately killed. Most insect parasitoids are wasps or flies, and many have a very narrow host range. The most important groups are the ichneumonid wasps, which mainly use caterpillars as hosts; braconid wasps, which attack caterpillars and a wide range of other insects including aphids; chalcidoid wasps, which parasitize eggs and larvae of many insect species; and tachinid flies, which parasitize a wide range of insects including caterpillars, beetle adults and larvae, and true bugs.[58] Parasitoids are most effective at reducing pest populations when their host organisms have limited refuges to hide from them.[59]

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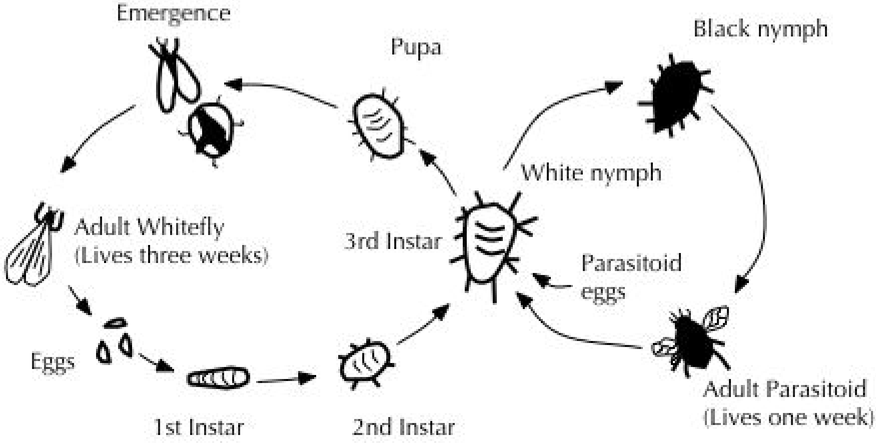
Encarsia formosa, widely used in greenhouse horticulture, was one of the first biological control agents



Life cycles of greenhouse whitefly and its parasitoid wasp *Encarsia formosa*

Parasitoids are among the most widely used biological control agents. Commercially, there are two types of rearing systems: short-term daily output with high production of parasitoids per day, and long-term, low daily output systems.[60] In most instances, production will need to be matched with the appropriate release dates when susceptible host species at a suitable phase of development will be available.[61] Larger production facilities produce on a yearlong basis, whereas some facilities produce only seasonally. Rearing facilities are usually a significant distance from where the agents are to be used in the field, and transporting the parasitoids from the point of production to the point of use can pose problems.[62] Shipping conditions can be too hot, and even vibrations from planes or trucks can adversely affect parasitoids.[60]

Encarsia formosa is a small parasitoid wasp attacking whiteflies, sap-feeding insects which can cause wilting and black sooty moulds in glasshouse vegetable and ornamental crops. It is most effective when dealing with low level infestations, giving protection over a long period of time. The wasp lays its eggs in young whitefly 'scales', turning them black as the parasite larvae pupate.[25] *Gonatocerus ashmeadi* (Hymenoptera: Mymaridae) has been introduced to control the glassy-winged sharpshooter *Homalodisca vitripennis* (Hemiptera: Cicadellidae) in French Polynesia and has successfully controlled ~95% of the pest density.[63]

The eastern spruce budworm is an example of a destructive insect in fir and spruce forests. Birds are a natural form of biological control, but the *Trichogramma minutum*, a species of parasitic wasp, has been investigated as an alternative to more controversial chemical controls.[64]

There are a number of recent studies pursuing sustainable methods for controlling urban cockroaches using parasitic wasps.[65][66] Since most cockroaches remain in the sewer system and sheltered areas which are inaccessible to insecticides, employing active-hunter wasps is a strategy to try and reduce their populations.

Pathogens

Pathogenic micro-organisms include bacteria, fungi, and viruses. They kill or debilitate their host and are relatively host-specific. Various microbial insect diseases occur naturally, but may also be used as biological pesticides.[67] When naturally occurring, these outbreaks are density-dependent in that they generally only occur as insect populations become denser.[68]

The use of pathogens against aquatic weeds was unknown until a groundbreaking 1972 proposal by Zettler and Freeman. Up to that point biocontrol of any kind had not been used against any water weeds. In their review of the possibilities, they noted the lack of interest and information thus far, and listed what was known of pests-of-pests - whether pathogens or not. They proposed that this should be relatively straightfoward to apply in the same way as other biocontrols.[69] And indeed in the decades since, the same biocontrol methods that are routine on land have become common in the water.

Bacteria

Bacteria used for biological control infect insects via their digestive tracts, so they offer only limited options for controlling insects with sucking mouth parts such as aphids and scale insects.[70] *Bacillus thuringiensis*, a soil-dwelling

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bacterium, is the most widely applied species of bacteria used for biological control, with at least four sub-species used against Lepidopteran (moth, butterfly), Coleopteran (beetle) and Dipteran (true fly) insect pests. The bacterium is available to organic farmers in sachets of dried spores which are mixed with water and sprayed onto vulnerable plants such as brassicas and fruit trees.[71][72] Genes from *B. thuringiensis* have also been incorporated into transgenic crops, making the plants express some of the bacterium's toxins, which are proteins. These confer resistance to insect pests and thus reduce the necessity for pesticide use.[73] If pests develop resistance to the toxins in these crops, *B. thuringiensis* will become useless in organic farming also.[74][72] The bacterium *Paenibacillus popilliae* which causes milky spore disease has been found useful in the control of Japanese beetle, killing the larvae. It is very specific to its host species and is harmless to vertebrates and other invertebrates.[75]

Bacillus spp.,[M 1] fluorescent Pseudomonads,[M 1] and Streptomycetes are controls of various fungal pathogens.[M 2]

Fungi

Green peach aphid, a pest in its own right and a vector of plant viruses, killed by the fungus *Pandora neoaphidis* (Zygomycota: Entomophthorales) Scale bar = 0.3 mm.

Entomopathogenic fungi, which cause disease in insects, include at least 14 species that attack aphids.[76] *Beauveria bassiana* is mass-produced and used to manage a wide variety of insect pests including whiteflies, thrips, aphids and weevils.[77] *Lecanicillium* spp. are deployed against white flies, thrips and aphids. *Metarhizium* spp. are used against pests including beetles, locusts and other grasshoppers, Hemiptera, and spider mites. *Paecilomyces fumosoroseus* is effective against white flies, thrips and aphids; *Purpureocillium lilacinus* is used against root-knot nematodes, and 89 *Trichoderma* species against certain plant pathogens.[M 3] *Trichoderma viride* has been used against Dutch elm disease, and has shown some effect in suppressing silver leaf, a disease of stone fruits caused by the pathogenic fungus *Chondrostereum purpureum*.[78]

Pathogenic fungi may be controlled by other fungi, or bacteria or yeasts, such as: *Gliocladium* spp., mycoparasitic *Pythium* spp., binucleate types of *Rhizoctonia* spp., and *Laetisaria* spp.

The fungi *Cordyceps* and *Metacordyceps* are deployed against a wide spectrum of arthropods.[79] *Entomophaga* is effective against pests such as the green peach aphid.[80]

Several members of Chytridiomycota and Blastocladiomycota have been explored as agents of biological control.[81][82] From Chytridiomycota, *Synchytrium solstitiale* is being considered as a control agent of the yellow star thistle (*Centaurea solstitialis*) in the United States.[83]

Viruses

Baculoviruses are specific to individual insect host species and have been shown to be useful in biological pest control. For example, the Lymantria dispar multicapsid nuclear polyhedrosis virus has been used to spray large areas of forest in North America where larvae of the spongy moth are causing serious defoliation. The moth larvae are killed by the virus they have eaten and die, the disintegrating cadavers leaving virus particles on the foliage to infect other larvae.[84]

A mammalian virus, the rabbit haemorrhagic disease virus was introduced to Australia to attempt to control the European rabbit populations there.[85] It escaped from quarantine and spread across the country, killing large numbers of rabbits. Very young animals survived, passing immunity to their offspring in due course and eventually producing a virus-

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resistant population.[86] Introduction into New Zealand in the 1990s was similarly successful at first, but a decade later, immunity had developed and populations had returned to pre-RHD levels.[87]

RNA mycoviruses are controls of various fungal pathogens.[M 2]

Oomycota

Lagenidium giganteum is a water-borne mold that parasitizes the larval stage of mosquitoes. When applied to water, the motile spores avoid unsuitable host species and search out suitable mosquito larval hosts. This mold has the advantages of a dormant phase, resistant to desiccation, with slow-release characteristics over several years. Unfortunately, it is susceptible to many chemicals used in mosquito abatement programmes.[88]

Competitors

The legume vine *Mucuna pruriens* is used in the countries of Benin and Vietnam as a biological control for problematic *Imperata cylindrica* grass: the vine is extremely vigorous and suppresses neighbouring plants by out-competing them for space and light. *Mucuna pruriens* is said not to be invasive outside its cultivated area.[89] *Desmodium uncinatum* can be used in push-pull farming to stop the parasitic plant, witchweed (*Striga*).[90]

The Australian bush fly, *Musca vetustissima*, is a major nuisance pest in Australia, but native decomposers found in Australia are not adapted to feeding on cow dung, which is where bush flies breed. Therefore, the Australian Dung Beetle Project (1965–1985), led by George Bornemissza of the Commonwealth Scientific and Industrial Research Organisation, released forty-nine species of dung beetle, to reduce the amount of dung and therefore also the potential breeding sites of the fly.[91]

Combined use of parasitoids and pathogens

In cases of massive and severe infection of invasive pests, techniques of pest control are often used in combination. An example is the emerald ash borer, *Agrilus planipennis*, an invasive beetle from China, which has destroyed tens of millions of ash trees in its introduced range in North America. As part of the campaign against it, from 2003 American scientists and the Chinese Academy of Forestry searched for its natural enemies in the wild, leading to the discovery of several parasitoid wasps, namely *Tetrastichus planipennisi*, a gregarious larval endoparasitoid, *Oobius agrili*, a solitary, parthenogenic egg parasitoid, and *Spathius agrili*, a gregarious larval ectoparasitoid. These have been introduced and released into the United States of America as a possible biological control of the emerald ash borer. Initial results for *Tetrastichus planipennisi* have shown promise, and it is now being released along with *Beauveria bassiana*, a fungal pathogen with known insecticidal properties.[92][93][94]

Target pests

Fungal pests

Botrytis cinerea on lettuce, by *Fusarium* spp. and *Penicillium claviforme*, on grape and strawberry by *Trichoderma* spp., on strawberry by *Cladosporium herbarum*, on Chinese cabbage by *Bacillus brevis*, and on various other crops by various yeasts and bacteria. *Sclerotinia sclerotiorum* by several fungal biocontrols. Fungal pod infection of snap bean by *Trichoderma hamatum* if before or concurrent with infection.[M 4] *Cryphonectria parasitica*, *Gaeumannomyces graminis*, *Sclerotinia* spp., and *Ophiostoma novo-ulmi* by viruses.[M 2] Various powdery mildews and rusts by various *Bacillus* spp. and fluorescent Pseudomonads.[M 1] *Colletotrichum orbiculare* will suppress further infection by itself if manipulated to produce plant-induced systemic resistance by infected the lowest leaf.[M 5]

Difficulties

Many of the most important pests are exotic, invasive species that severely impact agriculture, horticulture, forestry, and urban environments. They tend to arrive without their co-evolved parasites, pathogens and predators, and by escaping from these, populations may soar. Importing the natural enemies of these pests may seem a logical move but this may have unintended consequences; regulations may be ineffective and there may be unanticipated effects on biodiversity, and the adoption of the techniques may prove challenging because of a lack of knowledge among farmers and growers.[95]

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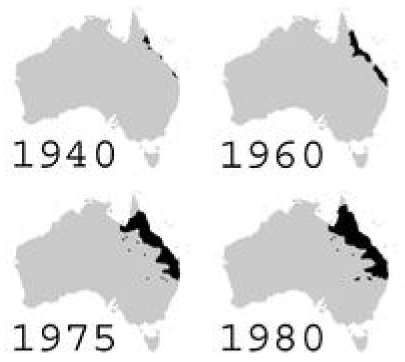
IV. CONCLUSIONS

Biological control can affect biodiversity[14] through predation, parasitism, pathogenicity, competition, or other attacks on non-target species.[96] An introduced control does not always target only the intended pest species; it can also target native species.[97] In Hawaii during the 1940s parasitic wasps were introduced to control a lepidopteran pest and the wasps are still found there today. This may have a negative impact on the native ecosystem; however, host range and impacts need to be studied before declaring their impact on the environment.[98]



Cane toad (introduced into Australia 1935) spread from 1940 to 1980: it was ineffective as a control agent. Its distribution has continued to widen since 1980.

Vertebrate animals tend to be generalist feeders, and seldom make good biological control agents; many of the classic cases of "biocontrol gone awry" involve vertebrates. For example, the cane toad (*Rhinella marina*) was intentionally introduced to Australia to control the greyback cane beetle (*Dermolepida albohirtum*),[99] and other pests of sugar cane. 102 toads were obtained from Hawaii and bred in captivity to increase their numbers until they were released into the sugar cane fields of the tropic north in 1935. It was later discovered that the toads could not jump very high and so were unable to eat the cane beetles which stayed on the upper stalks of the cane plants. However, the toad thrived by feeding on other insects and soon spread very rapidly; it took over native amphibian habitat and brought foreign disease to native toads and frogs, dramatically reducing their populations. Also, when it is threatened or handled, the cane toad releases poison from parotoid glands on its shoulders; native Australian species such as goannas, tiger snakes, dingos and northern quolls that attempted to eat the toad were harmed or killed. However, there has been some recent evidence that native predators are adapting, both physiologically and through changing their behaviour, so in the long run, their populations may recover.[100]

Rhinocyllus conicus, a seed-feeding weevil, was introduced to North America to control exotic musk thistle (*Carduus nutans*) and Canadian thistle (*Cirsium arvense*). However, the weevil also attacks native thistles, harming such species as the endemic Platte thistle (*Cirsium neomexicanum*) by selecting larger plants (which reduced the gene pool), reducing seed production and ultimately threatening the species' survival.[101] Similarly, the weevil *Larinus planus* was also used to try to control the Canadian thistle, but it damaged other thistles as well.[102][103] This included one species classified as threatened.[104]

The small Asian mongoose (*Herpestus javanicus*) was introduced to Hawaii in order to control the rat population. However, the mongoose was diurnal, and the rats emerged at night; the mongoose, therefore, preyed on the endemic birds of Hawaii, especially their eggs, more often than it ate the rats, and now both rats and mongooses threaten the birds. This introduction was undertaken without understanding the consequences of such an action. No regulations existed at the time, and more careful evaluation should prevent such releases now.[105]

The sturdy and prolific eastern mosquitofish (*Gambusia holbrooki*) is a native of the southeastern United States and was introduced around the world in the 1930s and '40s to feed on mosquito larvae and thus combat malaria. However, it has thrived at the expense of local species, causing a decline of endemic fish and frogs through competition for food resources, as well as through eating their eggs and larvae.[106] In Australia, control of the mosquitofish is the subject of discussion; in 1989 researchers A. H. Arthington and L. L. Lloyd stated that "biological population control is well beyond present capabilities".[107]

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Grower education

A potential obstacle to the adoption of biological pest control measures is that growers may prefer to stay with the familiar use of pesticides. However, pesticides have undesired effects, including the development of resistance among pests, and the destruction of natural enemies; these may in turn enable outbreaks of pests of other species than the ones originally targeted, and on crops at a distance from those treated with pesticides.[108] One method of increasing grower adoption of biocontrol methods involves letting them learn by doing, for example showing them simple field experiments, enabling them to observe the live predation of pests, or demonstrations of parasitised pests. In the Philippines, early-season sprays against leaf folder caterpillars were common practice, but growers were asked to follow a 'rule of thumb' of not spraying against leaf folders for the first 30 days after transplanting; participation in this resulted in a reduction of insecticide use by 1/3 and a change in grower perception of insecticide use.[109]

Related techniques

Related to biological pest control is the technique of introducing sterile individuals into the native population of some organism. This technique is widely practised with insects: a large number of males sterilized by radiation are released into the environment, which proceed to compete with the native males for females. Those females that copulate with the sterile males will lay infertile eggs, resulting in a decrease in the size of the population. Over time, with repeated introductions of sterile males, this could result in a significant decrease in the size of the organism's population.[110] A similar technique has recently been applied to weeds using irradiated pollen,[111] resulting in deformed seeds that do not sprout.[112]

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