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Integrated Pest Management: Sustainable Approach to Crop Protection

José Carlos Franco
Centro de Estudos Florestais, Instituto Superior de Agronomia, Universidade de Lisboa, Lisboa, Portugal

Synonyms

Integrated control; Integrated control protection; Integrated plant protection; Pest management

Definition

Integrated pest management (IPM) is a sustainable approach to crop protection using a decision support system to select pest control tactics, and integrate them into a management strategy, based on cost/benefit analysis that takes into consideration the economic, societal, and environmental impacts (Kogan 1998). The Food and Agriculture Organization of the United Nations (2005) and the European Union (EU Framework Directive 2009/128/EC 2009b) defined IPM as "all available plant protection methods and subsequent integration of appropriate measures that discourage the development of populations of harmful organisms and keep the use of plant protection products and other forms of intervention to levels that are economically and ecologically justified and reduce or minimise risks to human health and the environment; IPM emphasises the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms." Here the term pest refers to "any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products," following the International Plant Protection Convention (2010).

Introduction

The Origin of the Concept

The origin of the integrated pest management (IPM) is attributed to entomologists at the University of California (Stern et al. 1959), who suggested a new pest control approach (integrated control) to deal with the serious problems (e.g., secondary pest outbreaks caused by the elimination of natural enemies and pesticide resistance) caused by the widespread, and sometimes indiscriminate, use of broad-spectrum insecticides, observed after the discovery and successful application of dichlorodiphenyltrichloroethane (known as DDT), which stimulated the development and use of other organic pesticides. This new approach by Stern et al. (1959) to control pests that "combines and integrates biological and chemical control" stated that chemical control should be used only to complement biological control. The notions of "economic injury level" and "economic

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threshold" (Stern et al. 1959), considered the axioms of decision-making in pest control, also constituted the key elements of integrated control. The concept of integrated control was expanded to all available control measures, including cultural and mechanical measures (Franz 1961; van den Bosch and Stern 1962; Smith and Huffaker 1973). In the decade after, biological control became highly significant in this new approach to pest control (Perkins 1985).

Few years after the definition of integrated control by Stern et al. (1959), Australian entomologists presented the concept of "protective population management" (Geier and Clark 1961). This was later termed as "pest management" (Geier 1966) and defined as "intelligent manipulation of nature for humans' lasting benefit, as in wildlife management." This new concept of crop protection was based on A. J. Nicholson's ideas on insect population dynamics and the ecological aspects of pest control, as well as on the work of other ecologists, including C. S. Elton, A. G. Tansley, M. E. Solomon, H. G. Andrewartha, L. C. Birch, A. Milne, C. B. Huffaker, and D. Chitty (Clark et al. 1967).

The concepts of integrated control and pest management have evolved and merged into the concept of IPM (Smith et al. 1976; Poston et al. 1983; Pedigo et al. 1986; Van Emden and Peakall 1996). The term IPM was used for the first time by Apple and Smith (1976). However, Kogan (1998) refers to President Nixon of the USA who included a paragraph on IPM in a program for environmental protection in his message to the US Congress in February 1972. IPM has become the dominant paradigm involving a sustainable approach to crop protection.

Theoretical Aspects

Decision-making in integrated pest management commonly involves three questions, i.e., (1) IF (Is it necessary to apply curative control measures?), (2) WHEN (When should action be taken?) and (3) HOW (What type of control measures should be selected?), that can be answered based on the following concepts, respectively: economic injury level, economic threshold, and IPM tactics and strategies.

Economic injury level (EIL) is defined as the lowest population density of pest that will cause economic damage (i.e., the amount of injury which will justify the cost of artificial control measures, Stern et al. 1959). Economic damage was later clarified as the amount of damage for which the cost of suppressing pest injury equals the economic value of the potential crop loss caused by the pest population (Pedigo 1996). Although EIL is related to injury level, i.e., the level of injury to justify the application of control measures, it was defined as a function of pest density, as it is usually difficult to obtain direct measures of injury in field conditions (Pedigo et al. 1986; Funderburk et al. 1993; Pedigo 1996). The general model of economic injury level (Mumford and Norton 1984; Pedigo et al. 1986; Funderburk et al. 1993; Pedigo 1996) can be represented as follows:

$$\mathrm{EIL} = C/VIDK$$

where

€ = Euros

C = cost of management per area (e.g., €/ha)

V = market value per unit of production (e.g., €/kg)

I = injury units per insect per production unit (e.g., percent defoliation/insect/ha, expressed as a proportion)

P = pest population density (e.g., insects/ha)

D = damage per unit injury (e.g., kg lost/ha/percent defoliation)

K = proportionate reduction in potential injury or damage (e.g., 0.9)

The components of the models C, V, I, and D are affected by secondary variables, such as host-damage/injury and injury/insect-density relationships, and these are influenced by tertiary variables, which include weather, soil, biotic, and social features.

Several limitations have been identified in the use of EIL. For example, it cannot be applied in situations when (1) certain types of pests are involved, such as insect vectors of plant pathogens, (2) sampling methods are impractical, (3) only preventive control measures are available, and/or (4) multiple pests are involved (Poston et al. 1983; Mumford and Norton 1984; Pedigo et al. 1986; Ruesink and Onstad 1994; Pedigo 1996). Nevertheless, its simplicity, which has been object of criticism, is probably one of the main reasons for the persistence of the concept until today.

Economic threshold (ET) is the "density at which control measures should be determined to prevent an increasing pest population from reaching the EIL" (Stern et al. 1959) and corresponds to a threshold action point that defines the moment when a control tactic should be applied. It is assumed that exceeding the economic injury level is likely if pest populations reach the ET (Pedigo et al. 1986; Funderburk et al. 1993; Pedigo 1996). Table 1 summarizes the four evolving stages (Poston et al. 1983; Pedigo et al. 1986; Luckmann and Metcalf 1994; Pedigo 1996) defined for the ET implementation: (1) no, (2) nominal, (3) simple, and (4) comprehensive thresholds.

Integrated Pest Management: Sustainable Approach to Crop Protection, Table 1 Implementation of the economic threshold

Stage	Description
No threshold	Situations in which there are no defined ETs or they are not applicable, such as where only preventive tactics are available. It may include decision-making based on the recommendations delivered by regional plant protection services
Nominal thresholds	Empirical ETs are usually based on the experience of technical advisors at the regional level. These subjective ETs have been contributing to reducing pesticide treatments and are still common
Simple thresholds	Scientific ETs based on the EIL model
Comprehensive thresholds	Still under development: these ETs will be based on the effects of a pest community in the context of the entire production system. Implementation will be supported by computer-based information delivery systems

Integrated pest management **strategy** can be defined as "the overall plan to eliminate or alleviate a real or perceived pest problem," usually integrating one or, preferably, several **tactics**, i.e., the pest management methods used to implement a strategy, such as chemical and biological control (Pedigo 1996). The type of IPM strategy depends on four categories of the pest status: noneconomic, occasional, perennial, and severe (Pedigo 1996). The perennial and severe pests (known as key-pests) include the most serious and difficult pest problems, usually associated with high-value crops and/or high pest population densities. With noneconomic pests, the general equilibrium position (GEP) of the population is far below the economic injury level, and the highest fluctuations of their population numbers do not reach the EIL, and so do not cause economic damage. The occasional pests are the most common. Although their GEP is also below the EIL, population fluctuations occasionally reach the EIL. Perennial pests also have a GEP below the EIL but cause economic damage most years. Finally, in the case of severe pests, the GEP is above the EIL (Pedigo 1996). The Mediterranean fruit fly *Ceratitis capitata* and the California red scale *Aonidiella aurantii* are examples of key pests of citrus in the Mediterranean basin, whereas the black scale *Saissetia oleae* and the woolly whitefly *Aleurothrixus floccosus* are occasional pests (Franco et al. 2006; Garcia-Marí et al. 2018*)*. Different types of IPM strategies may be defined based on economic aspects and characteristics of the pest (Table 2) and implemented using different tactics (Table 3). The preventive (or prophylactic) tactics aim at avoiding potential pest problems. The therapeutic, curative, or responsive tactics intend to remediate a pest problem; they should be applied only after the occurrence of pest injury, if the ET has been reached.

Integrated pest management strategies should be ecologically sound and primarily based on preventive control tactics, whereas therapeutic control tactics, such as pesticides, should be used only if there are no alternatives. Particular attention should be paid to control tactics that enhance regulation ecosystem services such as biological

Integrated Pest Management: Sustainable Approach to Crop Protection, Table 2 Integrated pest management strategies (Pedigo 1996)

IPM strategy	Description
1. Do nothing	The strategy to follow in noneconomic pests and in occasional and perennial pests, when the ET is not reached
2. Reduce pest population density	The most common strategy; it may be implemented by just reducing population peaks during outbreaks, when the ET is reached (e.g., occasional pests), or by reducing the GEP (e.g., key pests). For example, pest population peaks may be reduced by selective insecticide treatments. GEP can be lowered with different control tactics, by reducing the environmental carrying capacity (e.g., crop rotation with nonhost plants) or the reproductive and/or survival potential of the pest population (e.g., biological control, sterile insect technique, mating disruption)
3. Reduce crop susceptibility to pest injury	One of the most effective and environmentally friendly strategies; it is focused on the plant; insect numbers are not reduced. For example, by using resistant plant cultivars or changing planting dates
4. Combine strategies 2 and 3	The most desirable strategy using integration of strategies

Integrated Pest Management: Sustainable Approach to Crop Protection, Table 3 Integrated pest management prevention and therapeutics (Pedigo 1996)

Tactic	Target	Objective	Examples
Prevention	Pest	Reducing the GEP	Some biological control tactics Crop rotation Sanitation Tillage Trap cropping Mating disruption Sterile insect technique
	Host plant	Reducing plant susceptibility	Rational irrigation and fertilization Disrupting crop and pest synchrony (e.g., modifying planting dates) Selecting tolerant/resistant plant varieties
Therapeutic	Pest	To stop pest population growth and the corresponding crop injury	Selective pesticides Inundative biological control Modifying harvest dates Pruning of infested branches in fruit trees

control of crop pests by their natural enemies (Tscharntke et al. 2007; Bommarco et al. 2013; Holland et al. 2016; Hatt et al. 2018). The communities of natural enemies are usually more diverse and abundant in structurally complex landscapes. These landscapes show higher functional biodiversity and may better provide the necessary resources the predators and parasitoids of crop pests need to complete their life cycles, such as alternative food (e.g., nectar, pollen), hosts/prey, or overwintering refuges (Rusch et al. 2010; Wäkers et al. 2013; Gardarin et al. 2018; Pollier et al. 2019). An approach to increment functional biodiversity in agricultural landscapes, thus promoting conservation biological control of crop pests, is through ecological infrastructures. Ecological infrastructures include any infrastructure existing within a farm, or in a range of about 150 m of the farm, with ecological value for the farm (Boller et al. 2004). Cover crops, hedges, field margins, riparian vegetation, and stone and wood piles are examples of ecological infrastructures that can provide the resources needed by the natural enemies of crop pests to survive and reproduce in agroecosystems. The effectiveness of biological control of crop pests depends on the abundance and diversity of their natural enemies within the crop fields. According to the International Organization for Biological and Integrated Control (IOBC)-West Palearctic Regional Section (WPRS) standards for integrated production, ecological infrastructures must cover at least 5% of the entire farm surface (excluding forests) to enhance functional biodiversity (Baur et al. 2011). Nevertheless, there is still lack of knowledge and cost-benefit analysis to define the necessary design of the management interventions (e.g., landscape diversification, decreased pesticide pressure) in order to attain a certain level of service (i.e., biological control) (Bommarco et al. 2013; Hatt et al. 2018).

The manipulation of odorscapes of insect pests is another promising crop protection tactic in alternative to pesticides, as volatile organic compounds (VOCs) in insect odorscapes are used by insects as chemical cues to locate different resources, such as food, mate, or enemies (Conchou et al. 2019). Mating disruption is an example of this approach, which is currently applied with success against several insect pests, in different crop systems, including the codling moth *Cydia pomonella* in apple and pear orchards, the European grape berry moth *Lobesia botrana* in vineyards, or the pink bollworm *Pectinophora gossypiella* in cotton (Miller and Gut 2015). Most of these insect pests are in the order Lepidoptera, but recently mating disruption formulations were also developed for the control of the vine mealybug *Planococcus ficus* in vineyards and the California red scale *Aonidiella aurantii* in citrus orchards (Benelli et al. 2019). Worldwide, mating disruption is estimated to be used in more than 800,000 ha for the management of agricultural insect pests (Miller and Gut 2015; Benelli et al. 2019). This control tactic is based on the release of synthetic sex pheromones, from dispensers used in high densities (200–3000 dispensers$\cdot$ha^{-1}) or through aerosol delivery systems, aiming to interfere and prevent mate finding and reproduction of the target insect pest (Miller and Gut 2015; Benelli et al. 2019; Conchou et al. 2019).

Implementing Integrated Pest Management in Europe

In 2009, the European Union published a set of new legislations, known as the "The Pesticides Package," including the (a) Directive 2009/128/EC on the sustainable use of pesticides, (b) Directive 2009/127/EC on machinery for pesticide application, (c) Regulation 1107/2009 on the placing of plant protection products on the market, and (d) Regulation 1185/2009 related with statistics on pesticides (European Union 2009a, b, c, d). According to the Directive 2009/128/EC, each member state must adopt a National Action Plan, setting up the objectives, targets, measures, and timetables to reduce the risks and impacts of pesticides and describing how the general principles of IPM (Table 4) are implemented. Recently, Barzman et al. (2015) discussed the implementation of those IPM principles aiming to help IPM practitioners in identifying efforts needed on research, education, and extension for a flexible, locally adapted, and practical IPM. The National Action Plans of the different member states are available in the DG SANTE webpage (European Commission 2018). An expert group consisting of representatives of 19 member states, the Commission, and EFSA elaborated a report identifying short- and long-term actions to increase the availability of low-risk plant protection products and speed up the application of IPM in EU (European Union 2016).

Two European organizations, the European and Mediterranean Plant Protection Organization and the International Organization for Biological Control/West Palearctic Regional Section, play a key role in the coordinated development of more sustainable plant protection solutions, through the implementation of IPM systems in Europe.

Integrated Pest Management: Sustainable Approach to Crop Protection, Table 4 Integrated pest management general principles (European Union 2009b; Barzman et al. 2015)

Principle	Description
1. Prevention and suppression	Combination of preventive tactics, e.g., crop rotation, resistant/ tolerant cultivars, balanced fertilization, hygiene measures, conservation biological control
2. Monitoring	Observation Forecast Diagnostic
3. Decision-making	Thresholds Multiple criteria
4. Nonchemical methods	Sustainable therapeutic tactics, e.g., biological and physical
5. Least side effects	When necessary, pesticides shall be as specific as possible and with the least side effects
6. Reduced pesticide use	For example, reduced doses, reduced application frequency, partial applications
7. Anti-resistance strategy	For example, use of multiple pesticides with different mode of action
8. Evaluation	Assessment of the entire process Adoption of new standards

European and Mediterranean Plant Protection Organization (EPPO, https://www.eppo.int/)

Founded in 1951, the EPPO is a Euro-Mediterranean intergovernmental organization for cooperation in plant protection that integrates 52 members. Its objectives include the (a) development of international strategies against the introduction and spread of alien pests, which are a threat to agriculture, forestry, and the environment in the Euro-Mediterranean region, and (b) use of safe and effective pest control methods. The EPPO has been responsible for the elaboration of standards related to plant protection products and plant quarantine, which constitute recommendations for National Plant Protection Organizations of EPPO members. It also promotes the exchange of information among member countries, based on information services and databases on plant pests, by organizing conferences/workshops.

International Organization of Biological Control (IOBC)/West Palearctic Regional Section (WPRS)

The IOBC (http://www.iobc-global.org/) was established in 1955 to promote environmentally safe methods for plant protection. The WPRS of IOBC (http://www.iobc-wprs.org/) is one of the six regional sections of IOBC, involving scientists and governmental, scientific, or commercial organizations from 24 countries in Europe, the Mediterranean region, and the Middle East. IOBC-WPRS fosters the research on and practical application of IPM by organizing meetings and symposia and offering training and information. Major activities include the development and standardization of testing methods for evaluating the secondary effects of pesticides, and pest damage assessment, as well as pest management modeling, and practical implementation of biological control and IPM in specific crops. IOBC-WPRS is organized in thematic working groups (WG), including IPM on fruit crops, grapevine, olive crops, citrus crops, oilseed crops, field vegetables, protected crops, stored products, and oak forest. It is involved with other specific subjects. These include pesticides and beneficial organisms, pheromones, and other semiochemicals. Multitrophic interactions in soil, microbial and nematode control of invertebrate pests, biological and IPM of plant pathogens, induced resistance in plants against insects and diseases, GMO's in integrated plant production, IPM of mite pests, and benefits and risks of exotic biological agents are also covered. IOBC-WPRS also contributes to the implementation of IPM through the production of scientific and technical publications, including an international journal on biological control (*BioControl*), the Proceedings of the WG meetings, books (Boller et al. 2004; Baur et al. 2011; Nicot 2011; Wijnands et al. 2012), and guidelines on integrated production for different crops (Malavolta and Calonnec 2016; Wijnands and Garcia-Marí 2016; Malavolta and Perdikis 2018; Alaphilippe et al. 2019; Malavolta et al. 2019).

Box 1. Integrated Pest Management Projects and Networks

Pesticide Action Network Europe (https://www.pan-europe.info/) involves 38 consumer, public health, and environmental organizations, trade unions, women's groups, and farmer associations. Its main objective is to support safe sustainable pest management tactics, eliminating the dependency on chemical control. PAN Europe aims at contributing for a substantial reduction in the use of pesticides in Europe.

ENDURE (European Network for the Durable Exploitation of Crop Protection Strategies) (www.endure-network.eu) brings together 15 partners from research, teaching, and extension institutions, with a special interest in IPM, within the general context of environmentally friendly and sustainable agriculture. ENDURE offers a range of tools for farm advisers, extension services, and trainers, including (1) ENDURE Network of Advisers (ENA), a forum for sharing knowledge on issues relating to crop production in general and plant protection in particular, all over Europe; (2) ENDURE Information Centre (ENDURE IC), for disseminating scientifically sound information on crop protection, for extension services, advisers, and researchers; and (3) ENDURE IPM Training Guide, for helping trainers to create their own training modules.

PURE (Pesticide Use and Risk Reduction in European Farming Systems with Integrated Pest Management) (http://www.pure-ipm.eu/) project was aimed at providing practical IPM solutions in major farming systems in Europe, in order to facilitate the implementation of EU Directive 2009/128/EC on the sustainable use of pesticides and related legislation (pesticides package legislation) while maintaining food quality.

NEFERTITI (Networking European Farms to Enhance Cross Fertilisation and Innovation Uptake Through Demonstration) (http://nefertiti-h2020.eu/) project comprising 32 partners, from 17 countries, aimed at establishing 10 interactive thematic networks, with 45 regional clusters of demo-farmers and actors involved (e.g., advisors, NGOs, industry, education, researchers, and policy-makers), including a thematic network on "pesticide use reduction in the production of grapes, fruits and vegetables."

Cross-References

- ▶ Agricultural Practices and Sustainability
- ▶ Agroecosystems: Overview
- ▶ Biodiversity and Ecosystems Management
- ▶ Ecoagriculture
- ▶ Invasive Species: Impacts and Control

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