Technical Bulletin No. …..

A Manual on
Potato Tuber Moth

ICAR- Central Potato Research Institute
Shimla-171 001 (HP)

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Contents

Potato Tuber Moth, *Phthorimaea operculella* (Zeller): Biology, Ecology, Surveillance and Phytosanitary Implications

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1. Introduction

Insect pests account for 16% of the crop losses in potato (*Solanum tuberosum* L.) worldwide (Oerke *et al.*, 1994), and reductions in tuber yield and quality can be between 30% and 70% for various insect pests (Raman and Radcliffe, 1992). Among the major pests is the potato tuber moth (PTM) *Phthorimaea operculella* (Zeller) (Lepidoptera, Gelechidae). PTM is known by several common names such as potato tuber moth, potato tuber worm, potato moth, potato leaf miner and tobacco leaf miner. Although two other species of tuber worms are known to infest potatoes i.e. *Tecia solanivora* (Povolny), the Guatemalan potato moth, and *Symmetrischema plaesiosema* (Turner) (= *Symmetrischema tangolis* (Gyen)), the Andean potato tuber moth; they are of importance to the specific regions. The Guatemalan potato moth is restricted to Central and Northwest South America where as the Andean potato tuber moth is restricted to South America, Southeast Australia, and Philippines. PTM is a major threat to potato production in most parts of the world. PTM infested tubers often become unfit for seed and table purposes or their market value is drastically reduced. Besides, the infested tubers become prone to several fungal and bacterial diseases resulting in rotting of tubers in the country stores (Saxena and Raj, 1979).

PTM was introduced into India in 1906 through seed potato imported from Italy (Lefroy, 1907). PTM has now established in many parts of the country, mostly the peninsular part and the hill states. The pest is restricted in distribution in India due to prevailing climatic conditions (scorching summer heat) and modern storage practices. It is therefore not likely to establish or cause any discernible economic damage in the Indo-Gangetic plains where the major chunk of seed potato is produced in India.

PTM attacks all vegetative plant parts of potato however; the damage done to tubers in storage is most severe. Losses up to 45% have been reported in country stores in the Republic of Yemen (Kroschel, 1995), 50% in the Andean region (Palacios and Cisneros, 1997), 90% losses in Kenya (Raman *et al.*, 1987), 86% in Tunisia, Algeria and Turkey; and 100% losses in India and the Philippines have been reported. In Egypt, potato tuber moth has caused up to 100% losses to potato plants in fields as well as in storage. In India, heavy infestation is reported from Himachal Pradesh, Maharashtra, Tamil Nadu, North eastern hill states and plateau region (Nair and Rao, 1972; Saxena and Raj, 1979; Raman and Palacios, 1982).

Wide tolerance to temperature and free international trade has lead to almost global distribution of PTM. Global climate change scenarios have alarmed the possibilities of the pest becoming more severe and expanding from its current habitat to newer area of potato production posing greater plant quarantine concerns (Sporleder *et al.*, 2008; Kroschel *et al.*, 2016). The zero tolerance to PTM in imported potatoes have increased the importance of the pest and its management many folds, particularly so in the aspiring exporters. In this bulletin, the fundamental aspects of the biology and ecology of PTM are discussed followed by detailed discussion on the phytosanitary implications of the pest with respect to potato exports and international trade. In the last section, a literature review on the management of PTM is given to bring forth the current status of knowledge and the difficulties faced while managing the pest.

2. Origin and Distribution

PTM most likely originated in Western South America along with its main host, the potato. PTM is a cosmopolitan pest, especially in warm temperate and tropical regions where host plants are grown and has been reported from more than 90 countries (Fig. 1). It occurs widely in Africa, Asia, Europe, Americas and Oceania (Australia and New Zealand) (Table 1).

In India, the damage has been reported from Pune (Maharashtra), Chhindwara (Madhya Pradesh), Kangra valley (Himachal Pradesh), Kumaon Hills (Uttarakhand), Ranchi (Jaharkhand), Bihar, West Bengal, Tamil Nadu, Karnataka, North-eastern hill states and plateau region (Saxena *et al.*, 1982). The incidence is more pronounced in locations where modern cold storage facilities are inadequate and potato is generally kept in country stores (Trivedi and Rajagopal, 1992). In the Indo-Gangetic plains, PTM is mostly absent due to scorching summer heat and nearly cent percent storage of potatoes in modern cold stores.

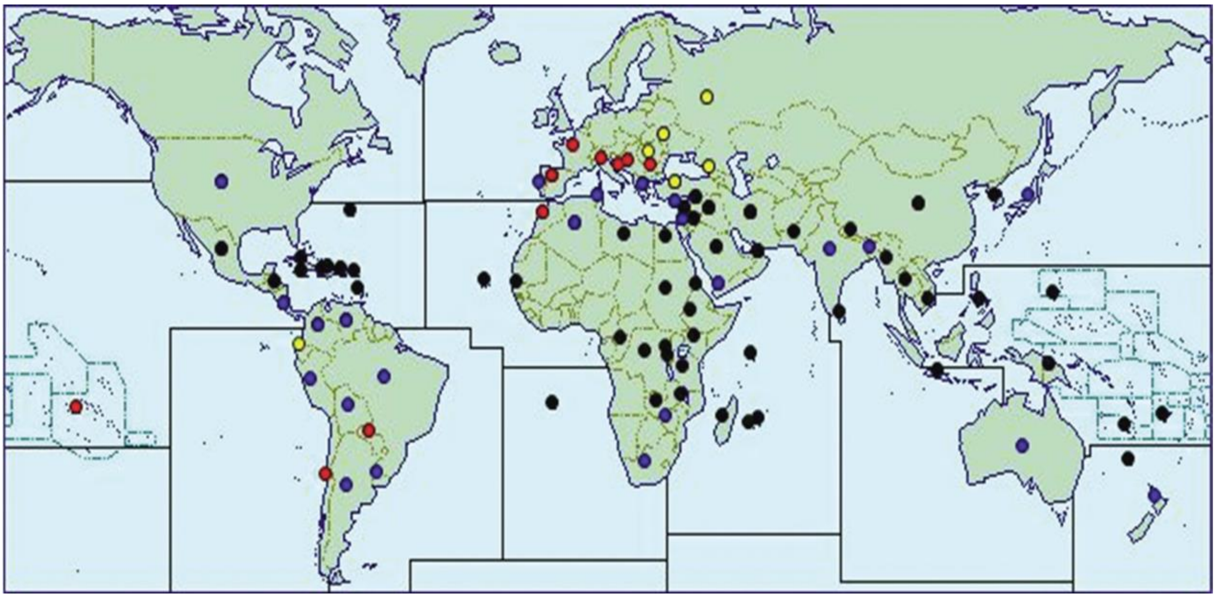

Fig. 1: Distribution of PTM in different regions of the world
(Source: http://www.cabi.org/isc/datasheet/40686#toDistributionMaps)

Table 1: Distribution and occurrences of PTM in different countries:

Sl. No.	Geographical Areas	Countries and Specific Regions
1.	**Oceania**	Australia (New South Wales, Northern Territory, Queensland, South Australia, Tasmania,Victoria, Western Australia), Fiji, French Polynesia, Guam, New Caledonia, New Zealand, Norfolk Island, Papua New Guinea.
2.	**Africa**	Algeria, Burundi, Cape Verde, Congo, DR Congo, Egypt, Cameroon, Eritrea, Ethiopia, Madagascar, Malawi, Mauritius, Morocco, Kenya, Libya, Reunion, Rwanda, Senegal, Seychelles, St. Helena, Sudan, South Africa, Tanzania, Tunisia, Uganda, Zambia, Zimbabwe
3.	**Asia**	Bangladesh, China (Guizhou, Yunnan), Georgia, India (Bihar, Himachal Pradesh, Karnataka, Madhya Pradesh, Maharashtra, Meghalaya, Orissa, Tamil Nadu, West Bengal), Indonesia (Java, Sulawesi, Sumatra), Iran, Iraq, Israel, Japan (Honshu, Kyushu, Shikoku), Jordan, Korea Republic, Lebanon, Myanmar, Nepal, Oman, Pakistan, Philippines, Saudi Arabia, Sri Lanka, Syria, Thailand, Turkey, Vietnam, Yemen
4.	**Europe***	Bulgaria, Croatia, Cyprus, France, Greece, Hungary, Italy (Sardinia, Sicily, Malta), Portugal (Azores, Madeira), Romania, Russia, Serbia, Spain (Canary Islands), UK (England and Wales), Ukraine
5.	**North America**	USA (Alabama, Arizona, California, Colorado, Delaware, Washington, DC, Florida, Georgia, Hawaii, Idaho, Illinois, Indiana, Iowa, Kansas, Kentucky, Louisiana, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, Nebraska, Nevada, New Jersey, New Mexico, New York, North Carolina, Ohio, Oregon, Pennsylvania, Rhode Island, South Carolina, South Dakota, Tennessee, Texas, Utah, Virginia, Washington, Wisconsin

6.	**Central America and the Caribbean**	Antigua and Barbuda, Bermuda, Costa Rica, Cuba, Dominican Republic, Haiti, Jamaica, Mexico, Puerto Rico, St. Vincent and Grenadines
7.	**South America**	Argentina, Bolivia, Brazil (Bahia, Goias, Minas Gerais, Parana, Rio Grande do Sul, Sao Paulo), Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela(Kroschel *et. al*., 2016)

*The European Plant Protection Organisation (EPPO) lists the pest as "present, widespread" in some southern European countries (e.g., Cyprus, Greece, Malta, mainland Portugal). "Few occurrence" or "restricted distribution" is recorded in Bulgaria, Croatia, France, Georgia, Italy, Romania, Russia, Serbia, Spain, Turkey, and Ukraine. In Albania, Portugal (Azores and Madeira), and the Canary Islands (Spain), PTM is recorded as "present" but no details about its status are available. In other European countries the pest is absent or intercepts only.

3. Host Range

Although PTM is primarily a pest of potato, it can also be found in other solanaceous plants such as brinjal (*Solanum melongena* L.), tomato (*S. lycopersicum*L.), black nightshade (*S. nigrum* L.), silver leaf nightshade (*S. elaegnifolium* Cav.), chilli pepper (*Capsicum frutescens* L.), tobacco (*Nicotiana tabacum* L.), cape gooseberry (*Physallis peruviana* L.), field ground cherry (*Physalis mollis* D.), prickly nightshade (*S. torvum* Sw.), jimson weed (*Datura stramonium* L.), *P. angulata* L., and *Brugmansia suavellens* Bersch. Though PTM can be found in all crops and weeds listed above, but it reproduces only on potato, tomato, brinjal and tobacco (Das and Raman, 1994). An exhaustive list of all reported host plants is given in Table 2.

Table 2: Alternate hosts of the potato tuber moth (Das and Raman, 1994)

Scientific name	Common name	Family	Field/labor-atory/green house	Status	Country
Amaranthus dubies Mart.	Amaranth	Amaranthaceae	Field	Economic	Zambia
Beta vulgaris L.	Sugar beet	Chenopodiaceae	Field	Economic	-
Capsicum annuum L.	Sweet pepper	Solanaceae	Field and laboratory	Economic	Italy, Bulgaria
C. frutescens L.	Chilli	Solanaceae	Field and laboratory	Economic	Australia
Cestrum parqui L'Herit.	Willow-leaved jessamine	Solanaceae	Field	Weed	-

Cynoglossum pictum Soland.	Hound’s tongue	Boraginaceae	Field, Green house	Weed	France
Cyphomandra betacea Sendt.	Tree-tomato	Solanaceae	Field	Economic	New Zealand
Datura feron L.	Datura	Solanaceae	Field	Weed	Rhodesia
D. mete1 L.	Hindu datura	Solanaceae	Field	Economic	Australia
D. stramonium L.	Thornapple	Solanaceae	Field	Weed	India, East Indies
D. suaveolens H. & B	Cow’s horn	Solanaceae	Field	Weed	India, East Indies
Fabiana imbricata Ruiz & Pav.	False heath	Solanaceae	Field	Weed	France
Hyoscyamus albus L.	White henbane	Solanaceae	Field	Weed	France
H. niger L.	Black henbane	Solanaceae	Field	Weed	Bulgaria
Linaria vulgaris Mill.	Toad flax	Scrophulariaceae	Field	Weed	France
Lycium europaeum Hort.	European boxthorn	Solanaceae	Field	Weed	France
L. halimifolium Mill.	Boxthorn	Solanaceae	Field	Weed	-
Lycopersicon esculentum Mill.	Tomato	Solanaceae	Laboratory	Economic	Cyprus, USA, Venezuela
Nicandra physalodes (L.) Gaertn	Apple of Peru	Solanaceae	Field, laboratory	Weed	Rhodesia
Nicotiana amplexicaulis	Tobacco	Solanaceae	Field, laboratory	Weed	Australia
N. debneyi Domin.	Tobacco	Solanaceae	Field	Weed	Australia
N. glauca Graham	Tree tobacco	Solanaceae	Field	Weed	Australia
N. glutinosa L.	Tobacco	Solanaceae	Field	Weed	Brazil
N. goodspeedii Wheeler	Tobacco	Solanaceae	Field	Weed	Australia
N. langsdorffii	Tabacco	Solanaceae	Field	Weed	Brazil
N. megalosiphon	Tobacco	Solanaceae	Field	Weed	Australia
N. nudicaulis	Tobacco	Solanaceae	Laboratory	Weed	Brazil

N. rustica L. var. *amarella*, *brasilia, humilis*	Aztec tobacco	Solanaceae	Field	Weed	Brazil
N. suaveolens Lehm	Native tobacco	Solanaceae	Laboratory	Weed	Australia
N. sylvestris S. & C.	Tobacco	Solanaceae	Field	Weed	France
N. tabacum L.	Common tobacco	Solanaceae	Field, laboratory	Economic	USA, Cyprus, Sri Lanka, USSR, Peru
Physalis angulata L.	Wild cape gooseberry	Solanaceae	Field	Weed	India, Rhodesia
P. minima L. var. indica	-	Solanaceae	Field	Weed	Australia
P. mollis Nutt.	Sun berry	Solanaceae	Field	Weed	USA
P. peruviana L.	Cape gooseberry	Solanaceae	Field	Economic	USA
Pyrus malus L.	Common apple tree	Rosaceae	Field	Economic	France
Solarium aculeatissimum Jacq.	Soda-apple	Solanaceae	Field	Weed	Australia
S. avicularae Forst. (syn. *S. laciniaium* Ait.)	Poroporo (Kangaroo-apple)	Solanaceae	Field	Economic	New Zealand
S. carolinense L.	Horse nettle	Solanaceae	Field	Weed	USA
S. commersoni Dun.	-	Solanaceae	Field	Weed	France
S. dulcamara L.	Bittersweet	Solanaceae	Field	Weed	France
S. elaeagnifolium Cav.	Silverlcaf nightshade	Solanaceae	Field	Weed	USA
S. esculentum Nec	Lady’s finger	Solanaceae	Field	Economic	-
S. incanum L.	Bitter apple	Solanaceae	Greenhouse	Weed	South Africa
S. indicum L.	-	Solanaceae	Laboratory	Economic	India
S. mammosum L.	Nipplc fruit	Solanaceae	Laboratory	Weed	Australia
S. mauritianum Stop.	-	Solanaceae	Laboratory	Weed	Australia

S. maglia Schlecht.	Darwin potato	Solanaceae	Field	Weed	France
S. melongena L.	Eggplant	Solanaceae	Field and laboratory	Economic	USA, Nepal
S. miniatum Bernh	Red nightshade	Solanaceae	Field	Weed	France
S. muricatum Ait..	Pepino	Solanaceae	Field	Economic	Australia
S. nigrum L.	Black nightshade	Solanaceae	Field	Weed	USA, East Indies
S. paniculatum	-	Solanaceae	Field	Weed	USA
S. sisymbriifolium Lam	Wild tomato	Solanaceae	Greenhouse	Weed	South Africa
S. sodomaeum L.	Apple of Sodom	Solanaceae	Field	Weed	Australia
S. torvum Swartz	Devil's fig	Solanaceae	Field	Weed	India, East Indies
S. verbascifolium L.	Mullein	Solanaceae	Field	Weed	Australia
Typha angustifolia L.	Small bulrush	Typhaccae	Field	Weed	France
Verbascum sinuatum L.	Mullein	Scrophulariaceae	Field	Weed	France
Xanthium strumarium L.	Cocklebur	Compositac	Greenhouse	Weed	South Africa

4. Biology and Life cycle

4.1 Growth Stages

Phthorimaea operculella has four life stages: egg, larva, pupa and adult.

Eggs

Eggs are 0.5 x 0.35 mm, spherical, translucent, and range in colour from white or yellowish to light brown (Fig. 2a). In the field, females lay their eggs on foliage, soil and plant debris, or exposed tubers; however, foliage is the preferred oviposition substrate.

Larvae

Larvae are usually light brown with a characteristic brown head. Mature larvae (≈ 0.94 cm long) may have a pink or greenish colour (Fig. 2b). No sexual dimorphism is observed until the 3rd larval stage where incipient sexual structures are visible; in the 4th larval stage, males are distinguishable from females by the presence of two elongated yellowish testes in the 5th and 6th abdominal segment.

Pupae

PTM pupae (≈ 0.84 cm long) are smooth and brown and often enclosed in a covering of fine soil and debris (Fig. 2c). There is a clear distinction between male and female pupae. Males can be recognized by the longer distance between the incision located between the 8th and 9th abdominal segment and the tip of the abdomen. There is also a gradual change in colour eye pigmentation. This information is helpful in estimating the age of the pupae.

Adults

Adults are small moths (≈0.94 cm long) with a wingspan of ≈ 1.27 cm. Forewings have dark spots (2-3 dots on males; "X" on females). Both pairs of wings have fringed edges. At rest, the wings are held close to the body, giving the moth a slender appearance (Fig. 2d). The moths live for 1 to 2 weeks, are crepuscular (active at dawn and dusk) and feed on nectar. The adults can move up to 0.25 Km between crops to infest plants or tubers. Long distance movement occurs when infested tubers are transported.

Fig. 2: The developmental stages of potato tuber moth, *Phthorimaea operculella*: (A) egg, (B) larva, (C) pupa, and (D) adults—female (left) and male (right). (Photo courtesy: CIP, Peru)

4.2 Life cycle

Copulation can take place 16 to 20 h after adult emergence; the duration of copulation ranges between 85 to 200 min. Adults are normally inactive during the day and oviposition occurs at night. Oviposition begins 1-3 days after emergence and continues for 4-9 days. Moths can crawl through soil cracks or burrow short distances through loose soil to find tubers and deposit eggs. Adults do not oviposit in the soil if potato foliage is available. The number of eggs laid and their longevity is directly related to their nutrition (Gubbaiash and Thontadarya, 1977; Fenemore, 1977, 1978).

PTM eggs are laid singly or in batches around buds, cracks, fissures or peeled potato skins. Eggs can be widely distributed in the soil but greater numbers are found around the base of the plants than between rows of plants. Females can lay 38 to 290 eggs with an incubation period of 5 to 34 days. No oviposition occurs above 36°C (Saxena and Raj, 1979; Isahagne and Md, 1978; Fenemore, 1979).

PTM passes through four larval stages. Length of time between instars is closely influenced by temperature. Larval period of 15 to 17 days is reported depending on the temperature. Normal larval activity (i.e. feeding and moulting) is reported from 11.1 to 39.4°C (Kroschel *et. al*., 2016). A pupal period of 6 to 9 days is recorded. PTM adults can potentially emerge from soil at depths up to 10.16 cm. Chauhan and Verma (1985) reported that 88% of males and 81% females emerged during photophase and remainder during scotophase. Once adults emerge, mating occurs and within a few hours females seek a potential host to lay their eggs on. Moths are fairly active at temperatures between 14.4 and 15.5°C; at 11.1°C they can crawl but do not fly (Choe *et. al*., 1980; Trivedi and Rajagopal, 1991). In north India, fecundity of 80-118 eggs is reported with a life cycle of 17-24 days in summer and 25-40 days in winter (Mukherjee, 1948; Verma, 1967).

After harvest, the larvae can potentially survive in volunteer potatoes, whereas eggs and pupae can survive in the soil, discarded potato piles, or even inside potato storing facilities. For example, eggs and pupae can be found in cracks in the walls of potato stores even after the potatoes have been consumed or sold.

4.3 Temperature dependent development

The life cycle depends strongly on prevailing temperature. For PTM, development is possible within the temperature range of <10ºC to approximately 32ºC. At 10°C, the median immature development time is about 215 days; however, with rising temperature the development time decreases and is about 17 days only at the pest's upper temperature limit of 32°C. The lower temperature threshold for survival in larvae is around 10°C (only about 4% of the newborn survive to the adult stage). Survival rates might be higher, even at lower temperatures, if the larvae are exposed to these low temperatures intermittently. Survival in eggs and pupae is generally >85% in the range of 17°–30°C but declines gradually with decreasing or increasing temperatures outside this range at 10°C about 78% and 65% in eggs and pupae, respectively. The lifespan of adults decreases as temperatures rise, from about 58 days at 10°C to about 8 days at 32°C. Oviposition peaks at temperatures of around 23°C, with about 164 (±40) eggs per female; 50% of the eggs are laid at this temperature within 3 days. The female fecundity rate is generally 50% (1:1 ♀:♂). Reproduction declines as temperature deviates from this optimum temperature and the median oviposition time declines as temperature rises and extends as temperature decreases. At 10°C reproduction per female reduces to 53 (±13) eggs, whereas 50% of the eggs are laid within 9.4 days. At 32°C only 37 (±9) eggs are produced per female, and the median oviposition time shrinks to <2 days. These simulations indicate that PTM is adapted to a wide range of temperatures, likely due to the wide range of environmental conditions found in the Andean region where the species evolved. Therefore, the pest has been able to establish in almost all tropical and subtropical potato production areas of the world (Briese, 1986; Ascerno, 1991).

4.4 Number of generations

Considering the duration period of each instar and its relationship to temperature, PTM can complete several generations per year. Six to eight generations a year are recorded in the tropical regions. In Chile and the U.S., all stages of PTM are found throughout the year with three to four generations (Trivedi and Rajagopal, 1992). Thirteen generations per year are reported in India (temperate areas), twelve in Iraq and two generations in Australia. This suggests a correlation between geographical location and number of PTM generations per year; locations with one crop per season will have 2 to 3 generations per year while locations with year-round crops will have several generations per year. As many as 8 to 9 generations in northern plains, 10-13 generations in peninsular area and 11 generations in north-eastern hill region are reported in a single year from India (Isahague and Md, 1978; Verma, 1967).

4.5 Means of movement and dispersal

Adults disperse in short “hopping” flights near the ground, with the aid of prevailing winds. The moths can move up to 0.25 km to infest plants or tubers, although it has been observed that they do not move from potato fields unless the field is harvested. Dispersal over long distances is on potato tubers, which has facilitated the spread of moths around the globe.

Pathway vectors

The pathway vectors of PTM include the infested tubers and possibly containers and packaging wood. It is recommended that the consignment be free of soil (tolerance limit: 1% for seed potatoes, 2% for ware potatoes) and plant debris.

Plant parts not known to carry the pest in trade/transport are; bark, flowers/ inflorescences/ cones/ calyx, fruits (i.e. pods), growing medium accompanying plants, leaves, roots, seedlings/ micro-propagated plants, stems (above ground)/ shoots/ trunks/ branches, true seeds and wood.

5. Nature of damage and Impact

The damaging stage of the pest is the larva which attacks potato by two ways; to the growing plants in the field and to the tubers in fields and in stores. Larvae feed on leaves throughout the canopy but prefer the upper foliage; larvae mine the leaves, usually leaving the epidermal areas on the upper and lower leaf surface intact. The affected leaf areas become transparent but due to the presence of excreta, they look brownish in colour (Fig. 3). The eggs are deposited on the leaves and the larvae immediately after hatching starts to mine the leaf and later may enter the petiole or cause a rolling or webbing of the leaf. Once the petiole is affected, the larva rapidly makes its way to the main stem. Whenever a larva works within the stem for several days before becoming mature, the terminal section of the plant usually dies (Fig. 4) (Saxena and Raj, 1979).

Larvae also move via cracks in the soil to find tubers, thus exposed tubers are predisposed to tuberworm damage. Larvae do not bore into tubers via stem. Some larvae make sub-epidermal channels while others tunnel directly through the tuber flesh. The tunnels get filled with excrement and fungi making the tubers un-sightful, unsafe and of no market value (Fig. 5). Larvae close to pupation drop from infested foliage to the ground and may burrow into the tuber to complete its life cycle. Ultimately, larvae will spin silk cocoons and pupate on the soil surface or in debris under the plant. Occasionally PTM pupae can be found on the surface of tubers, most commonly associated with indentations on the tuber eyes, but usually are not found inside tubers. Symptoms of PTM infestation are leaf blotches/mines, leaf webbing, mines in leaf petiole and stems and tunnels in the tuber (Graf, 1917; Cory, 1925; Manickavasgar, 1953).

Impact

- Economic loss due to tuber infestation in the field and storage
- International trade barrier due to zero tolerance to PTM infestation

Fig. 3: PTM damage to potato leaves; leaf mines (L) and leaf blotches (R)

Fig. 4: PTM larva mining potato stem (L), mature PTM larvae (R)

Fig. 5: PTM larvae damaging potato tubers

6. Phytosanitary Risks and Measures

PTM is such a global pest today that there are few countries where the species does not represent a potential external threat to agricultural production. Russia requires that potatoes imported from the European Union be free of PTM, and countries exporting potatoes to the Russian Federation, such as Belgium, carry out surveys, visual inspections, sampling, and lab confirmation to provide phytosanitary guarantee of potato shipments to be free of *P. operculella.* The zero tolerance level for PTM set for potato import by most of the countries needs the production areas be declared as PTM free (as per the guidelines of IPPC).

A "pest free area (PFA)", for PTM in this case, is described as an area in which a specific pest does not occur as demonstrated by scientific evidence and in which, where appropriate, this condition is being officially maintained" (IPPC). The establishment and use of a PFA by a national plant protection organization (NPPO) provides for the export of plants, plant products and other regulated articles from the country in which the area is situated (exporting country) to another country (importing country) without the need for application of additional phytosanitary measures when certain requirements are met. Thus, the pest free status of an area may be used as the basis for the phytosanitary certification of plants, plant products and other regulated articles with respect to the stated pest(s). The term "pest free areas" encompasses a whole range of types from an entire country which is pest free to a small area which is pest free but situated in a country where that pest is prevalent

The International Plant Protection Convention (IPPC) guidelines for the establishment and use of pest free areas (PFAs) under International Standards for Phytosanitary Measures are described briefly as follows.

6.1 Determination of a Pest Free Area

In principle, PFAs should be delimited in close relation with the occurrence of the PTM. In practice, however, PFAs are generally delimited by readily recognizable boundaries, considered to coincide acceptably with a pest's biological limits. These may be administrative (e.g. country, province or commune borders), physical features (e.g. rivers, seas, mountain ranges, roads) or property boundaries which are clear to all parties. For various practical reasons, it may also be decided to establish a PFA inside an area considered to be pest free, and thus avoid the necessity for exact delimitation of the true limits of the PFA.

6.2 Establishment and Maintenance of a PFA

There are three main components in establishing and maintaining a PFA. These include the systems to establish freedom, phytosanitary measures to maintain freedom and checks to verify freedom has been maintained.

i) **Systems to establish freedom**

Two general types of systems to provide data are recognized, though variations on or combinations of the two can be used. These are general surveillance and specific surveys. General surveillance involves utilizing all sources of data such as NPPOs, other national and local government agencies, research institutions, universities, scientific societies (including amateur specialists), producers, consultants, museums and the general public. Information may be obtained from scientific and trade journals, unpublished historical data and contemporary observations. Specific surveys may be detection or delimiting surveys. They are official surveys and should follow a plan which is approved by the NPPO concerned. The general plan for survey and surveillance of PTM is described in section 7.

ii) **Phytosanitary measures to maintain freedom**

Specific measures can be used to prevent the introduction and spread of a pest including (a) Regulatory action such as the listing of a pest on a quarantine pest list, specification of import requirements into a country or area, and restriction of the movement of certain products within areas of a country or countries including buffer zones; (b) Routine monitoring, and (c) Extension advice to producers.

iii) **Checks to verify freedom has been maintained**

In order to be able to verify the pest free status of a PFA and for purposes of internal management, the continuing pest free status should be checked after the PFA has been established and phytosanitary measures for maintenance have been put in place. The strength of the checking systems used should be related to the phytosanitary security required. These checks may include (a) *Ad hoc* inspection of exported consignments, and/or (b) Requirement that researchers, advisers or inspectors notify the NPPO of any occurrences of the pest and monitoring surveys.

6.3 Documentation and Review

The establishment and maintenance of a PFA should be adequately documented and periodically reviewed. Whatever the type of PFA, documentation should be available, as appropriate, on the data assembled to establish the PFA, various administrative measures taken in support of the PFA, delimitation of the PFA, phytosanitary regulations applied, and the technical details of surveillance, or survey and monitoring systems used.

It may be useful for an NPPO to send documentation about a PFA to a central information service (FAO or a regional plant protection organization), with all relevant details, so that the information can be communicated to all interested NPPOs at their request.

When a PFA requires complex measures for its establishment and maintenance to provide a high degree of phytosanitary security, an operational plan based on a bilateral agreement may be needed. Such a plan would list the specific details of activities required in the operation of the PFA including the role and responsibilities of the producers and traders of the country where the PFA is situated. The activities are reviewed and evaluated regularly and the results could form part of the plan.

In a country like India where PTM is known to be a pest of economic importance in some areas, the importance of official controls applied to contain a pest population is of paramount importance. An official delimiting survey maybe used to determine the extent of the infestation and, in addition, an official detection survey may be required in the uninfested area to verify absence of the pest. Strict phytosanitary regulations are required on the movement of commodities out of the infested area to the uninfested area to prevent spread of the pest.

7. Survey and Surveillance of PTM

Pest records are essential components of the information used to establish the status of a pest in an area. All importing and exporting countries need information concerning the status of pests for risk analysis, the establishment of and compliance with import regulations, and the establishment and maintenance of pest free areas. A pest record provides information concerning the presence or absence of a pest, the time and location of the observations, host(s) where appropriate, the damage observed, as well as references or other relevant information pertaining to a single observation. The reliability of pest records is based on consideration of the data in regard to the collector/identifier, the means of technical identification, the location and date of the record, and the recording/publication of the record. The determination of pest status requires expert judgment concerning the information available on the present-day occurrence of a pest in an area. Pest status is determined using information from individual pest records, pest records from surveys, data on pest absence, findings of general surveillance, and scientific publications and databases (Horne, 1993; Keller, 2003).

Pest status, as per the IPPC standards, is categorized into three types (a) *presence* of the pest – leading to determinations such as “present in all parts of the country, “present in some areas only”, etc. (b) *absence* of the pest – leading to determinations such as “no pest records”, “pest eradicated”, “pest no longer present”, etc. (c) *transience* of the pest – leading to determinations such as “non-actionable”, “actionable, under surveillance”, and “actionable, under eradication”.

To facilitate international cooperation among contracting parties in meeting their obligations in reporting the occurrence, outbreak or spread of pests, the National Plant Protection Organizations (NPPOs), or other organizations or persons involved in recording the presence, absence, or transience of pests, should follow good reporting practices. These practices concern the use of accurate, reliable data for pest records, the sharing of pest status information in a timely manner, respecting the legitimate interests of all parties concerned, and taking into account the pest status determinations.

A generalised protocol to determine the status of PTM is outlines as follows.

A. Plant and Tuber Damage in the field

- Select 10 villages randomly from each district (representing ca. 5000 ha)
- Select 3 fields (ca. 1 acre) per village
- Select 5 spots in each field, 4 along the margins and one in the centre
- Select 2 m row of plants randomly at each spot and
  i. Check the leaves from all stems (ca. 20) in the row for total number of PTM mines @ 3 leaves per plant
  ii. Inspect the stems for larvae and dissected 20 randomly selected stems for larval bores in them
  iii. Dig out 20 tubers per spot and inspect for tunnelling damage, by number
- The leaf and plant damage should be assessed two weeks after canopy closure and at haulm cutting.
- The field damage to tubers should be inspected at harvest.

B. Tuber damage during storage

i. Sample 200 tubers (as per the general scheme given in Table 3) of stored potato, randomly. Sample out tubers from the exposed surface and deep kept ones equally. Check for tunnelling damage by PTM, by number. Take a set of 200 tubers and incubate at 25°C for a week and check for the emerged caterpillar/pupae/adults, if needed.

ii. Growers in areas potentially impacted by PTM are encouraged to monitor insect numbers using pheromone traps. Pheromone traps are used to monitor populations in the field throughout the cropping season and in storage. The pheromone lure is loaded @ one pheromone capsule/trap. A lure load of 0.1 mg per trap for enclosed buildings, 0.3 mg/trap for most survey locations and 0.5 mg/trap for open fields is recommended. Either delta-styled corrugated plastic traps provided with sticky liners or water pan traps provided with a hood are used. Lures should be changed monthly but may be used longer, depending on environmental conditions; at cooler temperatures the longevity of the lures increases. The traps should be placed preferably on the field margins. The traps should be checked every few days for the caught moths. The trap liners/ water should be changed once a week.

    i. Field: installation of pheromone traps @ 10-12/ha for monitoring

    ii. Storage: installation of pheromone traps @ 4/100 m^3 for monitoring (Coll *et. al.*, 2000)

Infestation of potato tubers with eggs or young larvae of PTM is not always easy to detect; however, shipments infested with PTM generally show certain signs that clearly confirm the presence of the pest (e.g., adult moths flying around in a ship's potato hold, or silk cocoons visible on the tuber surface that may or may not include developing pupae). Such signs quickly confirm PTM infestation, which calls for immediate phytosanitary measures. It is recommended that countries where the pest does not yet prevail have in place a phytosanitary procedure (i.e., an officially prescribed method for performing inspections, tests, surveys, or treatments in connection with plant quarantine). These might include an official visual examination of plants and plant materials at arrival or of potatoes transported within the country to an area free of *P. operculella*. Surveys for detecting or verifying the pest can be carried out in a defined period of the year and defined potato production areas by using pheromone traps. Additional tests might confirm the presence of the moth in critical potato

Table 3: Suggested minimum sampling unit and inspection unit for various lot sizes of certified seed potatoes and ware potatoes*

Commodity	Size of lot (unit of examination)	Minimum sampling unit	Inspection unit
Certified seed potatoes	< 50 tonnes	5 bags	200 tubers
	50–200 tonnes	1 bag per 10 tonnes	200 tubers
	> 200 tonnes	1 bag per 10 tonnes	1 tuber per tonne
Ware potatoes	When the entire consignment is < 30 tonnes (e.g. shipping container, lorry, rail truck) and may consist of more than 1 lot	5 bags minimum - if more than 1 lot, bags selected in approximately equal numbers from each lot - if more than 5 lots, 1 bag minimum per lot	200 tubers
	30–50 tonnes	5 bags	200 tubers
	50–200 tonnes	1 bag per 10 tonnes	200 tubers
	> 200 tonnes	1 bag per 10 tonnes	1 tuber per tonne

*For bulk consignments or large bags, the whole consignment should be subdivided into identifiable lots, each of which then serves as a sampling unit. If this is not possible, the whole consignment should be taken as the sampling unit.

stocks. For example, potato tubers might be incubated in the laboratory at 24°C for several days and the samples checked for developing and emerging adults. If numerous adult moths are seen when a ship's hold is opened, prompt action is required to swat down the active moths immediately. In Europe, the EPPO's standard procedure includes an immediate application of a safe insecticide (e.g., a pyrethrin aerosol or fog). Later, the potato stocks are fumigated with methyl bromide (recommended dose is 16 g [CH_3Br] per m^3). Methyl bromide is being phased out internationally due to its ozone depleting effects under the Montreal Protocol. Many alternatives for methyl bromide are currently used, with more alternatives in development (e.g., propylene oxide and furfural), and although potatoes should be kept refrigerated (<10°C), if feasible the temperature should be allowed to rise above 10°C before the potatoes are fumigated. To avoid phytotoxicity problems, the potatoes especially new potatoes, which are most sensitive to *P. operculella* damage, should be thoroughly dried before fumigation. Complete degassing should be done rapidly after such treatments.

8. Management

An integrated management system is helpful in reducing PTM population in the field and stores. Different components are used from pre-sowing operations to storage of tubers for effective management of the pest population. The use of chemicals, however, is still the main foundation of *P. operculella* control worldwide (Shorey *et al.* 1967; Bacon *et al.* 1972; Hofmaster and Waterfield, 1972; Rondon *et al.*, 2007). No single control method provides adequate protection when their population is high. The precise knowledge on the behavioural and developmental biology, over seasoning and re-infestation cycle of the pest under different agro-climatic conditions is essential for formulating an effective IPM.

8.1 Monitoring of Potato Tuber Moth

Regular monitoring of PTM adult males with sex pheromone trap in field and storage is very useful to detect the early presence of the moth in order to take adequate control measures. The sex pheromone lure of PTM is loaded @ one pheromone capsule/trap. Either delta-styled corrugated plastic traps provided with sticky liners or water pan traps provided with a hood are used. Under field conditions, pheromone traps @ 10-12/ha and in storage facilities @ 4/100 m^3 are installed for monitoring purpose. Adults may be detected by light traps; however, light traps are not species-specific. The main components of *P. operculella* sex pheromone are: (E4,Z7) - tridecadienyl acetate (PTM1) and (E4,Z7,Z10)-tridecatrienyl acetate (PTM2) (Herman *et al.*, 2005; Rondon *et al.*, 2007).

Pheromone traps are used to monitor populations in the field to help time insecticide applications (Herman *et al.* 2005). The relationship between pheromone trapping and pest infestation in the foliage and tubers can help determine the selection of appropriate integrated pest management methods. Several authors found a positive relationship between the number of trapped adults and the density of larvae in the foliage and tuber (Shelton and Wyman, 1979a, b; Lall, 1989). Although treatment levels have not been established widely for *P. operculella*, a threshold of 15–20 moths per trap per night is recommended as a general threshold level. Something important to keep in mind is that *P. operculella* numbers vary highly from field to field and from area to area; thus, it is suggested that control management recommendations be based on field specific information (Rondon *et al.* 2007) and standard thresholds should be used solely as reference. Growers in areas potentially impacted by *P. operculella* are encouraged to monitor insect numbers using pheromone traps (Rondon *et al.* 2007).

8.2 Cultural Control: Some key aspects of the ecology of *P. operculella* are important in selecting best cultural practices to control this pest. Several biological and ecological studies support the effectiveness of one or more of these cultural practices. Some of the commonly adopted cultural practices for the management of PTM with varying degree of effectiveness are described as follows.

1. How this pest is distributed in and within the plant and field can guide control efforts. The distribution of foliage damage within field crops tends to be non-random since *P. operculella* tends to concentrate on the edges of the field facing the prevailing winds in a band parallel to the edge (Foot, 1979). Coll *et al.* (2000) found that larval density in foliage and tubers was higher at the margins of the field than in the center which is a typical characteristic of pests that move from area to area.
2. Tubers naturally mature as the potato plant senesces; however, improved methods keep potato vines healthier and greener; in addition, tuber maturation can be artificially induced by killing the potato vines mechanically, chemically, or with a combination of both. All these activities have an impact on *P. operculella* population infestation. Field observations support the premise that *P. operculella* prefer green foliage to tubers to oviposit and feed upon, and when foliage starts to decline, tuber infestation naturally increases. Thus, the time between desiccation and harvest is crucial. The longer the potatoes are left in the field after desiccation, the greater the likelihood of tuber infestation. Tuberworm moths and larvae are forced to go into the ground as vines are killed and, consequently, the risk of tuber damage increases (Rondon *et al.* 2007). Adults go into the soil via soil cracks to find shelter from the light and to lay their eggs on tubers, while larvae are forced there to find food. Tubers that are exposed or close to the surface are at high risk for tuberworm damage. Growers need to do everything possible to maintain more than 5 cm of soil over the tubers during the season (Rondon *et al.* 2007).
3. Female moths prefer dry soil for oviposition (Meisner *et al.* 1974) and survival of larvae increases with decreasing soil moisture content (Foot, 1979). Therefore, keeping the soil moist via overhead irrigation to avoid cracks in the soil, particularly later in the season when vines are beginning to die, reduces *P. operculella* tuber infestation. Research has shown that irrigating daily with 0.25 cm through a center pivot irrigation system from vine kill until harvest decreased *P. operculella* tuber damage and did not increase fungal or bacterial diseases (Rondon *et al.* 2007;Clough

et al., 2008). A possible explanation of the positive effect of daily irrigation application is that water closed soil cracks, reducing tuber access; thus tuberworm possibly died from lack of oxygen in the soil due to water saturation, and/or their mobility was reduced by wet soil decreasing their ability to find a tuber to infest. According to Foot (1979), larval survival is inversely related to soil moisture and tuber depth.

4. Saxena and Raj (1979) found that planting of healthy tubers reduced PTM infestation with planting tubers at a depth of 6 cm. The mean infestation of tubers was 9 and 18% when planted at 10 and 6 cm depth, respectively (Akhade *et al.*, 1970). Healthy seed tubers planted slightly deeper (10 cm) over the conventional planting depth (6 cm) followed by proper earthing up in times reduces PTM infestation up to 50%.
5. Infestation can be reduced by intercropping of potatoes with chillies, onion and pea (Lal, 1991).
6. As far as possible, harvested potatoes should be kept in cold storage. However, in case of non-availability of cold stores, only healthy tubers should be kept in cleaned and disinfected country stores.
7. Cull piles and volunteer potatoes should be eliminated to reduce overwintering stages, which are a source of next years' populations (Shelton and Wyman, 1980).
8. Further, covering dried leaves of lantana below and above potato heaps reduces damage by 90%. The leaves of eucalyptus and eupatorium are also effective; these dried leaves are normally effective about six months in Shillong condition (Lal, 1988).

8.3 Chemical Control

Chemical control of the potato tuberworm has posed a challenge for potato growers because eggs can be deposited on tubers after they are harvested (Rondon, 2007) and because insecticide efficacy on this pest has been unpredictable (von Arx *et al.* 1987, Berlinger 1992). Historically, a large number of insecticides have been found effective across locations. For example, spraying chlorofenvinphos (0.4 kg a.i./ha), acephate (0.5kg a.i./ha), quinalphos (0.375 kg a.i./ha), methamidophos 0.9 kg a.1./ha), phosalono (0.525 kg a.i./ha) and monocrotophos (0.6 kg a.i/ ha) provided effective control of PTM in field (Raj and Trivedi, 1987; Raj *et al.*, 1986). Dusting fields with carbaryl and parathion @ 2 kg a.i/ha 60 days after planting was also satisfactory (Awate and Naik, 1979; Awato and Pokharkar, 1976; Awate at al,, 1977). Spraying phosphamidon at 0.03% at 10-day intervals was effective in the field and dusting with malathion in storage (Gubbaiah and Thontadarya, 1975). Dipping tubers in

0.025% deltamethrin, 0.05% permethrin, 0.05% cypermethrin, 0.1 % fenvaierate, 1 and 2% dust of entrimfos (125 g/100 kg) was also effective and did not affect germination (Rai and Trivedi, 1987). The treatment of tubers before storage with phosalone, malathion, quinalphos and fenitrophion was effective for four months. Azinphossethyl was a superior ovicide and larvicide (Foot, 1974, 1976). In India, 0.4% fenvalerate dust @ 50 g/100 kg tubers was found effective (Trivedi, 1990). However, most of these chemicals are either banned for use or hav been rendered ineffective due to reisance development.

In the US, resistance to the pyrethroid esfenvalerate and the phenylpyrazole fipronil was documented in 2005 from field collected potato tuberworms from the Columbia Basin in the Pacific Northwest. Resistance to the organophosphate methamidophos was not detected in these strains (Doframaci and Tingey 2007). Recently, Clough *et al.* (2010) found that rotations of esfenvalerate and indoxacarb applications before and at vine kill were effective at reducing potato tuberworm damage. Those application timings are critical for effective control (Clough *et al.* 2008, 2010, Rondon 2010).

Researchers have determined that during the daytime the adult potato tuberworm moths rest on the bottom of potato leaves, becoming more active during the evening. Therefore, insecticide applications should coordinate with the evening peak of insect activity. Recently, the insecticides chlorantraniliprole and spinetoram have offered a more targeted and IPM-friendly option for lepidopteran control in potatoes. They have shown very good efficacy on potato tuberworm. These new narrow-spectrum insecticides are safer for the environment and less disruptive to natural enemies (Rondon, 2010).

8.4 Biological Control

Under current pest management practices in potatoes, especially in locations with an intensive agricultural production system centered on frequent calendar sprays of broad spectrum insecticides, the impact of natural enemies on *P. operculella* is unknown (Koss, 2003). In contrast, a lot of information regarding the biology and the potential of natural enemies (a.k.a. biological control agents) including parasitoids, predators, and diseases can be found in the literature. The advantage of using biological control agents is that they have no pre-harvest intervals, and are safer for application personnel, food supply and non-target organisms. Coll *et al.* (2000) reported five parasitic wasps and several predators of *P. operculella*. The parasitic wasps identified were *Diadegma pulchripes* (Kokujev), *Temelucha decorate* (Gravenhorst), both Ichneumonidae, *Bracon gelechiae* Ashmead (Braconidae), and two other unidentified Braconidae. The predators identified were *Coccinella septempunctata* Linnaeus (Coccinellidae), *Chrysoperla carnea* Stephens (Chrysopidae), *Orius albidipennis* (Reuter) (Anthocoridae), and four unidentified species of Formicidae (Coll *et al.* 2000). *Copidosoma koehleri* Blanchard and *Apanteles subandinus* Blanchard are believed to be excellent parasitoids of *P. operculella* worldwide along with Trichogramma (Rondon, 2010). In South America, *Copidosoma* and *Apanteles* wasps controlled *P. operculella* field populations (Redolfi and Vargas, 1983).

In India, several parasitoids, predators and pathogens were recorded (Ayyar, 1928; Ullah, 1939, 1941; Usman, 1957; Dalaya and Talgeri, 1971; Nair and Rao, 1972). Thirteen indigenous parasitoids of PTM were reported from Karnataka, where 20-30% parasitization was observed during 1965-1967. Among these, *Chelonus curvimaculatus*, *Bracon gelechiae*, *Apanteles* spp., *Pristomerus vulnergator* and *Bracon* sp. were the most abundant, causing 4-17% parasitism under field conditions (Nair and Rao, 1972). Two parasitolds, *Nythobla* sp. and *Chelonus curvimaculatus* were found to give good control in Pretoria (Watmough *et al.*, 1973). *Diadigma niolliplum* caused 2.5-5.0% parasitisation in Shimla (Saxena *et al.*, 1980). Field releases of *Bracon hebator* resulted in 12% parasitization of PTM larvae in Bangalore (Divakar and Pawar, 1979). A number of exotic parasitoids have been introduced to India. *Copidosoma akoehleri*, an egg and larval parasitoid gave 28-61% parasitazation in Maharashtra (Dalaya and Patil, 1973). Continuous release of these parasitoids was required for effective suppression of PTM (Khandger *et al.*, 1979). *Orgllus jennieae* and *Apanteles subandinus* produced up to 60% and 17% parasitization respectively (Saxena and Raj, 1979; Chaudhary *et al.*, 1983). *Blattisocius keegani* was found to suppress PTM in peninsular India (Trivedi and Rajagopal, 1991).

8.5 Microbial Control

Insect diseases caused by bacteria, viruses, and nematodes have been developed as microbial pesticides to control insect pests not only in the field but also in the storage. However, microbial control of *P. operculella* is not yet developed for massive commercial use although some authors have indicated the potential use of those pathogens in the future. In fact, some small scale tuberworm control by microbes has been already used successfully (Kroschel *et al.* 1996a, b; Sporleder *et al.* 2001, 2005; Sporleder, 2003). Amongst the microbial pesticides, the granulosis virus and the bacterium *Bacillus thuringiensis* have been shown to have potential for successful control of PTM.

The granulovirus attacking the common potato tuber moth (PTM) *P. operculella* (i.e., PhopGV) has the potential to play a key role in managing the moth, especially for protecting stored tubers (Sporleder 2003). Histopathology studies showed the fat body and epidermis are the main tissues infected by the virus and that the virus morphogenesis is similar to other GVs, with the exception that small vesicles appear between mature granules (Lacey *et al.* 2011a). Infected *P. operculella* larvae can be recognized by their opaque, milky white color, and by their behavior. Infected larvae do not respond vigorously when disturbed. The effect of the virus on the larvae is lethal since they fail to pupate; however, very high dosages of PhopGV can cause death by toxicosis within 48 hours. In 1984, researchers of the International Potato Center (CIP) in Lima, Peru, identified PhopGV from a potato store in Lima (Raman and Alcázar 1988) and initiated research on the beneficial role of PhopGV in an IPM program (Alcázar *et al.* 1991, 1992b, Alcázar and Raman 1992, Lagnaoui *et al.* 1995). CIP has developed a simple technique for multiplication and formulation of the virus (CIP 1993). A dust formulation, produced by selecting and grinding virus-infected larvae from damaged potato tubers and then mixing them with ordinary talc, has been used at the rate of 5 kg/tonne of stored potatoes (20 infected larvae per kg). Research showed that the granulovirus would reduce damage in stores by 91% and 78%, 30 and 60 days after application (Raman and Alcázar 1990), respectively. The virus, in this dust formulation, has been promoted successfully for protecting farmers' home-stored potatoes in Peru, Bolivia, Ecuador, Tunisia, and Egypt by using low-cost facilities for propagation (Gelernter and Trumble 1999). Good protection of treated tubers in non-refrigerated storage using PhopGV products has been reported by several researchers. A substantial amount of successful testing of PhopGV has been conducted on stored tubers in the Andean countries (CIP, 1992; Zeddam *et al.* 2003) and in several countries in the Middle East, Northern Africa, and Asia (Amonkar *et al.* 1979; Setiawati *et al.* 1999). Protection of tubers generally lasted several months. Lacey *et al.* (2010) showed that PhopGV in a liquid formulation can be used for protecting tubers stored in refrigerated warehouse conditions. However, the high amount of virus-infected larvae needed for field applications is a limiting factor. In addition, studies of PTM field populations have, in some cases, revealed natural *Phop*GV incidence levels as high as 35–40% (Kroschel 1995, Laarif *et al.* 2003). Several authors have shown that the infestation of potato tubers at harvest can be significantly reduced by effectively controlling PTM on the foliage during the growing season (Arthurs *et al.* 2008). One of the main constraints using *Phop*GV in the field is its rapid inactivation due to solar (ultraviolet, UV) radiation. As with other modelling studies on microbial control agents (Anderson *et al.* 1982), Sporleder and

Kroschel's modeling results indicated that for long-term control of the pest population and for inoculative augmentation, subsequent applications causing moderate infection in the host population may be better than a single hit with greater virulence (Sporleder *et al.* 2004).
The only bacterium that has been evaluated for PTM control is *Bacillus thuringiensis* (Bt). Bt var. kurstaki (Btk) is the most commonly used against lepidopterous insects. Natural isolates of Bt were found within the PTM's native range in Bolivia (Hernández *et al.* 2005). Bt has been reported effective for control of PTM infestations under field conditions (Awate and Naik 1979, Broza and Sneh 1994, Kroschel and Koch 1996, Arthurs *et al.* 2008). However, repeated applications have been required because Bt is degraded by UV light from the sun, and rain washes it onto the soil (Salama *et al.* 1995). Three consecutive applications of Bt (Bio-T™) at 8-day intervals were required to control PTM in an infested tomato crop in Israel (Broza and Sneh 1994). A high application volume (500 L/ha) was used to bring the active ingredient into the tunnels in the leaves where young larvae were mining. In field plot tests in India, foliar application of Bt (Thuricide® at 2–5 kg/ha) at 15-day intervals beginning 60 days after planting was almost as effective at controlling PTM infestations as parathion and carbaryl (Awate and Naik 1979). In the Republic of Yemen, PTM infestations are very high. Kroschel (1995) tested Bt (DiPel®) over two seasons at two concentrations (0.2% and 0.3%) with three and four applications per potato season. In the control treatments, PTM leaf infestation reached 26 and 35 mines per plant. Until the plant-yellowing stage, Bt application reduced PTM leaf infestation by 41% and 54% and final tuber infestation at harvest by 23% and 10%, respectively, compared to the control treatment. Arthurs *et al.* (2008) reported fairly good control of very high PTM populations with Btk, but several applications of 1.12 kg/ha were required throughout the growing season.

Bt has also been widely tested to control PTM infestations under laboratory and storage conditions. In Egypt, another Bt preparation (DiPel® 2X at 0.3% concentration) was also reported to be very effective to protect tubers in stores, eliminating PTM infestation compared with 100% infestation in untreated controls 60 days after treatment (Farrag 1998). In Tunisia, an integrated control approach comprising Bt applied at the beginning of the storage period in combination with cultural control (early harvest) eliminated the reliance on parathion sprays (von Arx *et al.* 1987). In cases when tubers had a high initial infestation (over 20%), Bt was replaced with a synthetic pyrethroid (permethrin). In tests in Indonesia, tubers treated with Btk (Thuricide at 2 g/L) caused 79% larval mortality after 4 months of storage compared with 58% mortality of larvae on foliage in a screenhouse (Setiawati *et al.*

1999). In other studies, Btt (0.2% Bactospeine® wettable powder (WP) 16,000 IU/mg) was reported ineffective at protecting tubers in storage, resulting in as much tuber damage as in untreated controls (Das *et al.* 1992). Formulation of Bt with various carriers has been reported by several researches to improve Bt activity and/or to reduce product costs. Btk mixed with fine sand dust containing quartz provided effective control in tuber storage in the Republic of Yemen (Kroschel and Koch 1996). A very low proportion, 40 g *Btk* mixed with 960 g sand, applied to 1 tonne of stored potatoes proved to be efficacious. This treatment also controlled 96% of larvae that were already inside tubers. In Peru, Raman *et al.* (1987) reported that *Btk* (DiPel) was effective in reducing feeding damage in storage when applied as a dust formulation. Formulation of *Btk* with various diluents was effective against neonate larvae. Arthurs *et al.* (2008) demonstrated that tubers treated with 37.5 mg *Btk* WP mixed in talcum or diatomaceous earth/ kg tuber before infestation resulted in 99% PTM larval mortality. Different inert materials alone were tested to determine their capacity for providing additional physical protection against moth attack in stored potatoes (Das and Rahman 1997, Mamani *et al.* 2011). Tubers treated with talc only were better protected against *P. operculella* and *S. tangolias* attack than tubers treated with kaolin, lime, or sand (Mamani *et al.* 2011).

There is not much information regarding other beneficial agents such as the fungi *Nosema* which can cause up to 80% infection rate and cause shortening oflarval life and lowering of reproduction capacity of adults (Allen and Brunson, 1947). Other fungi such as *Metarhizium anisopliae*, *Beauveria bassiana* and *Muscodor albus* have potential for control of larvae (Lacey and Arthurs, 2005; Mercier and Smilanick, 2005).

8.6 Botanicals

Seed extracts of *Ocimum bacillicum*, rhizomes of *Acorus calamus* and leaves of *Ageratum conyzoides* have been reported as toxic to the larvae of PTM by Panday *et al.* (1982). Acetone extracts of *Anisomeles malabarica, La-bipinnata, L. gibsonl and Ocimum americanum* havealso proved to be oviposition deterrants. Extracts of *L. gibsoni* have shown good ovicidal activity (Sharma *at al.*, 1981a, 1981b). Covering potato tubers in storage with a 2.5 cm layer of dry *Lantana* leaves, sawdust, wheat straw and dry soap nut leaves were effective in reducing the infestation (Khan, 1944), as observed with *Eucalyptus* and neem. Covering tubers with ash or ash mixed with lime was also effective (Lal, 1945). In India, stored tubers covered with dried and chopped leaves of Lantana reduced tuber damage from 99 to 5%; likewise, Eucalyptus leaves reduced tuber damage to 8 % (Lal, 1988). In Peru, *Eucalyptus globosus*, *Lantana camara*, and *Mintho stachys*, both in dried and powdered forms were effective in controlling *P. operculella* (Raman *et al.*, 1987).

Commercial products of Azadirachtin (extracts of neem) revealed activity against PTM in laboratory experiments (Chatterjee, 2005). Kroschel and Koch (1996) reported high efficacy of a water extract of neem applied in storages. In growing potato fields, light irrigation every 4 days and mulching with neem leaves during the latter 4 weeks before harvest were effective for reducing tuber infestation at harvest (Ali, 1993).

8.7 Semiochemicals and Attract-and-Kill Approach

Commercial sex pheromones are available for PTM species, *P. operculella*. Their use for disrupting mating in this species appears an economically feasible method of control in non-refrigerated potato store rooms, and helps to monitor the pest during storage. Kroschel and Zegarra (2010) developed an attract-and-kill strategy for the PTM species *P. operculella* and *S. tangolias*. The attract-and-kill product (attracticide) consisted of pure pheromones and cyfluthrin as the contact insecticide, formulated with plant oils and ultraviolet screens. The product was applied in droplet sizes of 100µL and resulted, under controlled conditions, in 100% mortality of adult male moths, without reduction in efficacy of the formulation for a period of 36 days. The preliminary field experiments indicated good potential using the attract-and-kill technology in potato (Kroschel and Zegarra 2007). Droplet densities of 1 drop per 4 m^2 reduced the number of daily PTM male catches compared with the untreated control by 83.8%. Such treatment corresponds to an application of 1.25 g cyfluthrin as active ingredient to kill the moths per hectare, which is 32-fold less than the recommended field rate of Baythroid® EC 100 for controlling lepidopteran pests. The use of this product seems appropriate for use in developing countries where plant protection is usually done with knapsack sprayers. The application of single droplets applied by using an appropriate hand disperser requires less manpower than the application of chemical pesticides, which involves transportation of water (about 250–500 L/ha) to the field.

8.8 Cold Storage

Potatoes should be stored at temperatures ranging between 7.2 to 10°C. Since *P. operculella* does not develop at temperatures below 5°C (Al-Ali *et al.* 1975), it does not cause economic problems in cold storage (Roux *et al.* 1992; Keasar *et al.* 2005). In theory, it might be possible for the tuberworm to survive such temperatures which slow their developmental rate; however, eggs, larvae or pupae held in cold storage for long periods of time are incapacitated

(Langford and Cory, 1932). In developing countries, potatoes are stored in sheds, under trees or in unrefrigerated warehouses (Hossain *et al.* 1994; Keasar *et al.* 2005). Tuberworm damage under those conditions can be devastating (up to 100% in some cases).

8.9 Treatment with CIPC in country stores

Chlorpropham (isopropyl-N-(3-chlorophenyl) carbamate) commonly known as CIPC used for sprout suppression is reported to be effective against PTM damage in country stores when applied @ 30 ppm. For fogging, 35-40 ml of CIPC is required for treating one ton of potatoes, similar to the recommended for sprout suppression. There was negligible PTM incidence (0.3-2.8 %) in CIPC treated tubers compared to 3.6-27.6 % in untreated tubers kept under country stores. The degree of infestation was slight (<3 feeding holes/tuber) in CIPC treated tubers having PTM infestation, whereas it was medium (3-4 holes) to serve (< 4 holes) in untreated tubers lots. In the samples collected from treated stores, the residue was within the permissible limit (Chandla *et. al*., 2008).

Conclusion

The Potato Tuber Moth is an important pest of potato in India and worldwide. The infestation starts from the field which can be carried to the stores or the traditional storage structures can themselves be a source of the pest. The larvae damage the leaves and stems and later on infest the exposed tubers in the field. The damage is more severe in the stored tubers. Also, international trade barrier due to zero tolerance to PTM infestation makes this pest economically very important. Infestation in the modern cold storage facilities is unlikely however; the traditional storage structures are susceptible to pest infestation. Regular monitoring and timely application of control tactics can help manage the pest in field as well as stored tubers. A thorough knowledge of the distribution, host range, biology and ecology of the pest is necessary before developing management practices. It is difficult to achieve effective control by a single method when the infestation is very high. In later stages, the selective use of recommended insecticides and mass trapping with sex pheromones should be put into practice. In storage, it is necessary to remove damaged tubers before storing: Sex pheromones may be used for monitoring and mass trapping. Zero tolerance level for PTM is set for potato import by most of the countries thus straining the prospects of international trade. Although the pest is restricted in distribution in India due to prevailing climatic conditions and modern storage practices, surveillance and efficient management of PTM is essential starting right from the fields to the storage structures and strict adherence to phytosanitary measure is absolutely necessary to keep the pest from spreading to new areas.

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