Manual of Potato tuber moth, *Phthorimaea operculella* (Zeller)

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Insect pests are one of the major constraints to commercial production of potato in India. According to Simpson (1977), potato is damaged by at least 101 arthropod pests, of which Potato tuber moth (PTM) *Phthorimaea operculella*, (Lepidoptera, Gelechidae) is an important pest occurring globally in temperate and tropical regions (Radcliffe, 1982). It is known by several common names as potato tuber moth, potato tuber worm, potato moth, potato leaf miner and tobacco leaf miner. It was first referred as potato grub in 1854 by H. Berthen and subsequently described as *Gelechia operculella* (Zeller, 1873). The genus was revised in 1902 and 1931 and assigned to the genus Phthorimaea in 1964. Although two other species of tuberworm can be found, *Tecia solanivora* (Povolny), the Guatemalan potato moth, restricted to Central and Northwest South America, and *Symmetrischema plaesiosema* (Turner) (=*Symmetrischema tangolis* (Gyen)), the Andean potato tuber moth, found in South America, Southeast Australia, and Philippines, they are of importance to the specific regions. It was introduced into India in 1906 through seed potato imported from Italy (Lefroy, 1907).PTM has now established in parts of Maharashtra (winter and rainy crops), Plateau of Karnataka, Tamil Nadu, Mid hills especially in Kangra valley of Himachal Pradesh, North eastern region – Meghalya, Parts of Madhya Pradesh (Malva region) and some parts of Uttarakhand, Bihar and Chhattisgarh where modern cold storage facilities are inadequate and potato is generally kept in country stores (Trivedi and Rajagopal, 1992). Infected tubers often become unfit for seed and table purposes or their market value is reduced. Beside that such infested tubers become prone to several fungal and bacterial diseases resulting in rotting of tubers in the country stores (Saxena, 1979).

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 2008; Kroschel *et al.*, 2013).

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Economic Importance

PTM is a major pest of potato particularly the stored tubers. Losses in stored potatoes ranging from 50% in Yemen and Peru; 86% in Tunisia, Algeria and Turkey; 90% in Kenya; and 100% in India and the Philippines have been reported (Aryal and Chuleni, 2015). In Egypt, potato tuber moth has caused up to 100% losses to potato in fields as well as in storage. PTM has been found to cause 30-70% infestation in country stores in India where modern cold storage facilities are inadequate. Up to 100% tuber infestation is reported from Karnataka (Nair and Rao, 1972; Saxena and Raj, 1979; Raman, 1982).

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).

In South Central Asia, PTM was introduced in 1906 to Bombay, India, from Italy. 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, 1983).

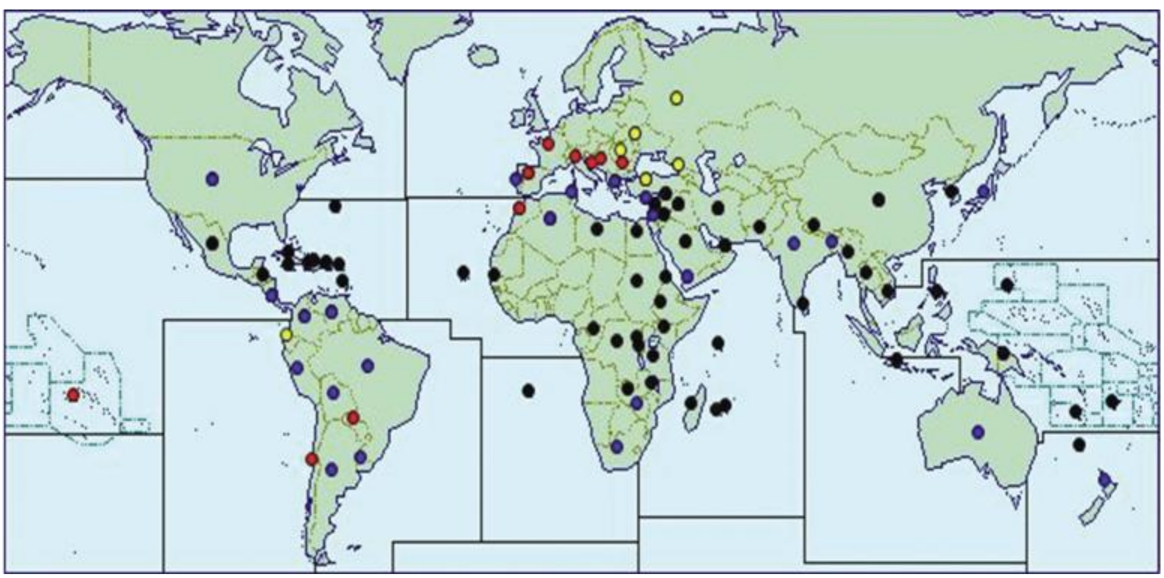


Fig1. Distribution of PTM in different countries of the world (Source: (http://www.cabi.org/isc/datasheet/40686#toDistributionMaps)

The moth occurs in almost all tropical and subtropical potato production systems in Africa and Asia, as well as those in North, Central, and South America. Although it can still be of economic significance in subtropical regions of southern Europe (e.g., Italy), the long cold winters in temperate regions generally restrict its permanent establishment and development and hence reduces its pest status.

Table-1 Distribution and occurance of PTH in different countries: 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

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

Asia Bangladesh, China (Guizhou, Yunnan), Georgia, **India (Bihar, Gujarat, Himachal Pradesh, Karnataka, Madhya Pradesh, Maharashtra, Meghalaya, Orissa, Punjab, Tamil Nadu, Uttrakhand**, 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

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

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

Central America and the Caribbean Antigua and Barbuda, Bermuda, Costa Rica, Cuba, Dominican Republic, Haiti, Jamaica, Mexico, Puerto Rico, St. Vincent and Grenadines

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)

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 (*Solanum lycopersicum* L.), black nightshade (*S.*

nigrum L.), silverleaf 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, 1992)).

Table 2 Alternate hosts of the potato tuber moth (Das and Raman, 1992))

Scientific name	**Common name**	**Family**	**Field/ laboratory/ greenhouse**	**Status**	**Country**
Amaranthus dubies Mart.’	Amaranth	Amaranthaceae	Field	Economi c	Zambia
Beta vulgaris L.’	Sugar beet	Chenopodiaceae	Field	Economi c	-
Capsicum annuum L.	Sweet pepper	Solanaceae	Field and laboratory	Economi c	Italy, Bulgaria
C. frutescens L.	Chilli	Solanaceae	Field and laboratory	Economi c	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	Economi c	New Zealand
Datura feron L.	Datura	Solanaceae	Field	Weed	Rhodesia
D. mete1 L.	Hindu datura	Solanaceae	Field	Economi c	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	Solanaceae	Field	Weed	USA, East

	nightshade				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

Growth stages/Life stages

Adults

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

Eggs

Eggs are 0.5x0.35 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.

Pupa

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 8^{th} and 9^{th} abdominal segment and the tip of the abdomen. There is also a gradual change in colour eye pigmentation. This information can help estimate the age of the pupae

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). Photos: Courtesy of CIP.

Nature of damage

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-3B). The egg is 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 (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 unsightful, unsafe and of no market value. 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).

Fig-3 (A) Leaf Minor Damage (B) PTM Damage

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 (38-290 eggs) around buds, cracks, fissures or peeled potato skins. The hatching time depends closely on temperature. 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. Other authors reported a range between 3 to 9.9 days depending on temperature. 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 molting) 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. 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; Shaheen, 1983; Trivedi and Rajagopal, 1991a).In North India, 13 generation a year were found. Fecundity varied from 80-118 eggs and life cycle took 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. Chauhan and Verma (1985) reported that 88% of males and 81% females emerged during photophase and remainder during scotophase.

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).

Number of generations

Considering the duration period of each instar and its relationship to abiotic factors such as 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, 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 (Isahague and Md, 1978: Verma, 1967).

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 include** Infested tubers and possibly containers and packaging wood.

Plant parts not known to carry the pest in trade/transport

- 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
- Wood

Changes in distribution, establishment and abundance with climate change

Current predictions on rising temperature due to climate change suggests that the species is likely to extend its range of permanent establishment northwards and southwards in the Northern and Southern hemispheres, respectively, and into higher altitudes in tropical and subtropical mountain regions. In temperate regions, the risk of establishment significantly increases in the northern United States (Columbia basin), southern Europe (including France and Italy), Central Asia, New South Wales and Victoria in Australia, and in southern Chile and Argentina in South America. In all tropical mountain regions (Andes, Atlas, Alborz in Iran, and Hindu Kush Himalaya), the boundaries for permanent establishment can be expected to move several 100 masl in altitude. Also, with its wide range of temperature adaptation, PTM might establish in all potato production zones within the 10°C isotherm in the Northern and Southern hemispheres. Owing to global warming, the number of generations per year and the overall abundance and activity of the pest can be expected to increase in all potato production zones worldwide (Cory, 1925; CIE, 1968; Coll *et. al*.2000).

Impact

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

1. **How to differentiate from other moths**Leaf mining symptoms of PTM may be confused with those of potato leaf miner.
2. The PTM pheromone trap may attract few other moth species in addition to PTM; those can be sorted with the help of following recognition features of PTM.
    - Moths are about 1 cm long.
    - The predominant colour of the tuberworm is light brown. There are grey and black scales on the wings, but most scales are brown, and scales on head lay flat.

- There are two large dark spots on each front wing Most specimens have a third smaller dark spot on each front wing behind the large spots.
- The antennae are always light brown. Most of the non-PTW in traps have black or grey antennae.
- Thorax has three longitudinal stripes
- Abdomen has pale fuzzy area apically (Fig. 2& 3).

International experience: 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. The pest intercepts occasionally on imported plant material in European countries. It is doubtful, however, whether the species survives severe cold winters of temperate countries, and thus phytosanitary measures in Europe are not regulated by EU law. The European Plant Protection Organisation (EPPO) does list 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. Russia requires that potatoes imported from the EU 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.*

In Africa, CIP carried out an assessment of the PTM distribution through extensive trapping using sex pheromones in Ethiopia, Kenya, Rwanda, Burundi, Tanzania, and Zaire during 1987–1988. The survey revealed that the range of the pest had extended from the north into the central regions of the continent and demonstrated severity of infestations in Zaire, Burundi, and Kenya. Today the pest is known to be widespread in northern Mediterranean countries (Algeria, Egypt, Morocco, Tunisia); East Africa (Ethiopia, Kenya, Tanzania, Uganda, Rwanda); and Southern Africa. In Egypt (the Nile Delta), the moth is recognized as a significant pest in tomato as well. The moth has been reported in Cape Verde, Cameroon, DR Congo, Eritrea, Madagascar, Malawi, Mauritius, Libya, Reunion, Senegal, Seychelles, St. Helena, Sudan, Zambia, and

Zimbabwe, but no detailed information about its status and distribution is available. In other African countries the presence of PTM has not been confirmed.

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 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.

Survey and Surveillance

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 is outlined in this standard in terms of three categories incorporating various final determinations: - *presence* of the pest – leading to determinations such as "present in all parts of the country, "present in some areas only", etc. - *absence* of the pest – leading to determinations such as "no pest records", "pest eradicated", "pest no longer present", etc.- *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 in this standard.

Requirements for the establishment of PTM free areas:

1.1 Determination of a Pest Free Area

The delimitation of a PFA should be relevant to the biology of PTM. This will affect the scale at which it is possible to define a PFA and the types of boundaries by which it can be delimited. 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.

1.2 Establishment and Maintenance of a PFA

There are three main components in establishing and maintaining a PFA. These are:

- systems to establish freedom
- phyto sanitary measures to maintain freedom
- Checks to verify freedom has been maintained.

The nature of these components will vary according to the:

- Biology of the PTM including:
  - Its survival potential
  - its rate of reproduction
  - its means of dispersal
  - the availability of host plants etc.
- Relevant PFA characteristics including its:
  - Size
  - Degree of isolation
  - Ecological conditions
  - Homogeneity etc
- Level of phyto sanitary security required as related to the assessed level of risk, according to the pest risk analysis conducted.

1.2.1 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
- Specific surveys

General surveillance

This 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
- Contemporary observations.

Specific surveys

These may be detection or delimiting surveys. They are official surveys and should follow a plan which is approved by the NPPO concerned.

1.2.2 Phytosanitary measures to maintain freedom

Specific measures can be used to prevent the introduction and spread of a pest including:

- Regulatory action such as the:

· listing of a pest on a quarantine pest list

· Specification of import requirements into a country or area

· Restriction of the movement of certain products within areas of a country or countries including buffer zones

- Routine monitoring
- Extension advice to producers.

The application of phyto sanitary measures to maintain pest freedom status is only justified in a PFA, or any portion of a PFA, in which ecological conditions are suitable for the pest to establish.

1.2.3 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 phyto sanitary measures for maintenance have been put in place. The strength of the checking systems used should be related to the phyto sanitary security required. These checks may include:

- Ad hoc inspection of exported consignments
- Requirement that researchers, advisers or inspectors notify the NPPO of any occurrences of the pest and monitoring surveys.

1.3 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
- 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 would be reviewed and evaluated regularly and the results could form part of the plan.

2. Specific requirements of different types of PFA

The term “pest free area” encompasses the spectrum of all types of PFA. For convenience, the requirements of PFAs are discussed by dividing them into three arbitrary types of pest free areas:

- An entire country
- An uninfested part of a country in which a limited infested area is present
- An uninfested part of a country situated within a generally infested area.

In each of these cases, the PFA may, as appropriate, concern all or part of several countries. The specific requirements for the three types of pest free areas are discussed below.

2.1 Entire Country

In this instance, entire country freedom for a specific pest applies to a political entity for which an NPPO has responsibility.

Requirements may include the following.

2.1.1 Systems to establish freedom

Both data from general surveillance and from specific surveys are acceptable. They are different in that they may provide for different kinds or degrees of phyto sanitary security.

2.1.2 Phyto sanitary measures to maintain freedom

These may include those listed in section 1.2.2.

2.1.3 Checks to verify freedom has been maintained

These may include those listed in section 1.2.3.

2.1.4 Documentation and review These may include those items listed in section 1.3.

2.2 Uninfected Part of a Country in Which a Limited Infested Area is Present

In this instance, the distribution of the pest is limited to part of a country as determined by the NPPO. Official controls are applied to contain a pest population. The PFA may be all or part of the un infested area. Requirements may include the following.

2.2.1 Systems to establish freedom

Normally PFA status is based on verification from specific surveys. An official delimiting survey may be used to determine the extent of the infestation and, in addition, an official detection survey may be required in the un infested area to verify absence of the pest. General surveillance (see 2.1.1 above) may also, if appropriate, be applied to the un infested part of a country in which a limited infested area is present.

2.2.2 Phyto sanitary measures to maintain freedom

These may include those listed in section 1.2.2. With this type of PFA, phyto sanitary regulations may also be required on the movement of commodities out of the infested area to the un infested area to prevent spread of the pest as noted in 1.2.2.

2.2.3 Checks to verify freedom has been maintained

These may include those listed in section 1.2.3. Monitoring surveys are of more significance in this type of PFA than for that involving an entire country.

2.2.4 Documentation and review

Documentation may include supporting evidence describing official controls such as survey results, phyto sanitary regulations and information on the NPPO as noted in section 1.3.

2.3 Un infested Part of a Country Situated Within a Generally Infested Area

This type of PFA is an area, within a generally infested area, which has been made (or shown to be) free from a specific pest. It is maintained pest free so that an exporting country can use this status as a basis for phytosanitary certification of plants and/or plant products. In certain cases, a PFA may be established within an area whose infestation status has not been based on specific surveys. The PFA should be adequately isolated in relation to the biology of the pest.

Requirements should include the following.

2.3.1 Systems to establish freedom

Delimiting and detection surveys would be required for this type of PFA.

2.3.2 Phyto sanitary measures to maintain freedom

These may include those listed in section 1.2.2. With this type of PFA, phyto sanitary regulations may also be required on the movement of host material out of the infested area to the un infested area to prevent spread of the pest as noted in 1.2.2.

2.3.3 Checks to verify freedom has been maintained

These may include those listed in section 1.2.3. Ongoing monitoring surveys are a likely requirement with this type of PFA.

2.3.4 Documentation and review

Documentation may include supporting evidence describing official controls such as survey results, phyto sanitary regulations and information on the NPPO as noted in section 1.3. As this type of PFA is likely to involve an agreement between the exporting and the importing country, its implementation would need to be reviewed and evaluated by the NPPO of the importing country.

1. 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 10 plants randomly at each spot and
        - I. Check the leaves from 10 stems for total number of PTM mines @ 3 leaves per plant
        - II. Inspect the stems for larvae and dissected 10 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.
2. Tuber damage during storage

    Sample 200 tubers per 1000 quintals 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 subset of 20 tubers and incubate at 25°C for a week and check for the emerged caterpillar/pupae/adults, if needed.

3. Growers in areas potentially impacted by PTM are encouraged to monitor insect numbers using pheromone traps. The PTM pheromone lure is a combination of two chemicals (E4, Z7)-tridecadienyl acetate (PTM1) and (E4, Z7, Z10)-tridecatrienyl acetate (PTM2). 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. 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.
    - Field: installation of pheromone traps @ 10-12/ha for monitoring
    - Storage: installation of pheromone traps @ 4/100 m^3 for monitoring (Coll *et. al.*, 2000)

<u>Management of Potato Tuber Moth :</u>

Several approaches for the development of an integrated pest management system for *P. operculella* are available. However, considering that most of the economic damage by this insect occurs when the insect infests tubers, early attempts to control this pest should focus on cultural methods. Deeper seed planting, hilling the rows, irrigation and early harvest are a few of the methods suggested to prevent tuber infestation (Langford and Cory, 1932; Langford 1933; Shelton and Wyman, 1979a) since these methods discourage egg-laying moths from finding oviposition substrates. 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). No single control method provides adequate protection when their population is high. The precise knowledge on the behavioral and developmental biology, over seasoning and re infestation cycle of the pest under different agro-climatic conditions is essential for formulating an effective IPM. Comprehensive studies have been made in the north eastern hills by Lal (1988, 1989, 1990 ,1991).

Monitoring of Potato Tuber Moth: Adult male moth is attracted by pheromone, concentrated quantities of the female "scent", impregnated in a rubber septum in the center of a sticky liner in the trap. According to Herman *et al.* (2005), two chemicals have been identified as the main component of *P. operculella* sex pheromone: (E4, Z7) - tridecadienyl acetate (PTM1) (Roelofs *et al*. 1975) and (E4, Z7, Z10)-tridecatrienyl acetate (PTM2) (Persoons *et al*. 1976); both chemicals were synthesized, blended, and tested (Voerman and Rothschild, 1978; Raman, 1988). Since some other insects, including other Gelechiidae moths could be trapped in the sticky liners, they should be changed once a week for easy viewing of adult moths. Lures should be changed monthly but may be used longer, depending on environmental conditions; at cooler temperatures the longevity of the lures increases (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); but others did not find such a correlation (Rondon, *et al*. 2007). Although treatment levels have not been established widely for *P. operculella*, California recommends a threshold of 15–20 moths per trap per night 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). Several researchers have tested different types of traps (Kennedy 1975; Bacon *et al*. 1976; Raman 1988; Salas *et al.* 1991; Tamhankar and Harwalkar, 1994). In New Zealand, Herman *et al.* (2005) tested the use of water traps, which caught the greatest number of moths per trap as compared to the "DeSIRe" sticky traps (delta shaped), "A traps" (cylinder-shaped), and funnel traps. They concluded that the delta trap was the most suitable for commercial use. Coll *et al*. (2000) used pheromone traps plus poison bait placed on the ground at 50 m intervals in single rows. Based on Herman *et al*. (2005) findings, the recommendation in the U.S. Pacific Northwest has been to place at least one delta trap per potato field, beginning after canopy closure (Rondon *et al*. 2007). Note that soil type has an effect on the number of moths caught per trap; in Israel, almost twice as many moths were caught in pheromone traps located in sandy soil than in lose fields (Coll *et al*. 2000). Above 20 traps/ha would be required to reduce the PTM population in the fields. If the incidence is more, especially in dry summer months, the number of traps may be extended up to 40 traps/ ha. Under Indian storage conditions, PTM population was reduced by 85% if such traps were used to catch the male moths (Saxena *et al*. 1982). Chauhan and Verma (1985) reported that 88% of males and 81% of females emerged during the photophase and the remainder during scotophase. The peak period was between 0700 to 0900 h and 0900 to 1100 h for males and females, respectively during summer. Emergence took longer in winter than in summer suggesting less activity of moths at lower temperature.

Cultural Control: Some key aspects of the ecology of *P. operculella* are important in selecting best management practices to control this pest. How this pest is distributed in and within the plant and field can guide control efforts. The relationship between quality plant and insect preference helps choosing best control method. Succulent plants attract more tuber worm than wilting, non-irrigated plants (Yathom, 1968), and the distribution of foliage damage within field crops tends to be non-random (Foot, 1974a, 1976b, 1979) 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 (Reed, 1971; Foot, 1979; Gilboa and Podoler, 1995). Plants on the edges are exposed to wind and solar radiation that leads to drier conditions that are attractive to *P. operculella* females for oviposition (Meisner, 1969; Meisner *et al*. 1974; Gilboa and Podoler 1995; Coll *et al*. 2000). Some experiments suggest that a low number of moths foraged beyond 100–250 m to infest tuber or plants (Cameron *et al*. 2002). In the U.S. Pacific Northwest most of the potatoes are vine-killed right before harvest, thus it is recommended that *P. operculella* control take place at or after vine-kill (Rondon *et al.* 2007).

There are several cultural methods that have been reported to reduce *P. operculella* population. These include the elimination of cull piles and volunteers, timing of vine kill, soil moisture at and after vine-kill, time between desiccation and harvest, rolling hills and covering hills, and cultivar selection (Rondon *et al*. 2007). In Tunisia, practices like deep seeding, hilling up, early harvest, irrigation until harvest, good sorting of tubers at harvest and rapid harvesting prevent tuber infestation (Von Arx *et al*. 1987a; BenSalah and Aalbu, 1992). Several biological and ecological studies support the effectiveness of one or more of these cultural practices. 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. Tuber worm 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). Female moths prefer dry soil for oviposition (Meisner 1969; 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. It also has been shown that exposed tubers are more prone to tuber worm infestation (Von Arx *et al.* 1987a). Foot (1979) indicated that tuber infestation occurred 2–4 weeks before harvest and all infested tubers were covered with no more than 3 cm of soil. Research has found that rolling of potato hills in sandy soil caused soil to slough off the hill, which resulted in increased *P. operculella* damage and therefore is not recommended in areas with sandy soils. Covering hills with 2.5–5.1 cm of soil immediately after vine-kill, which can be accomplished with a rotary corrigator, has been shown to significantly reduce tuber infestation (Rondon *et al.* 2007; Clough *et al*. 2008). Also, cull piles and volunteer potatoes should be eliminated to reduce overwintering stages, which are a source of next years' populations (Shelton and Wyman, 1980). 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). When plants were grown under furrow and sprinkler irrigation in California, the former had 58 times more damage than the latter (Shelton and Wyman, 1979). In fact first instar larvae of PTM could not move through wet soil but could penetrate 12.5 cm in dry soil (Mahajanan and Mogal, 1978). 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%. Besides, infestation can be reduced by intercropping of potatoes with chillies, onion and pea (Lal, 1991). 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. 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 normally effective about six months in Shillong condition (Lal, 1988).

Chemical Control: Studies suggest that insecticides that are effective against foliar infestation by *P. operculella* may not prevent tuber infestation (Bacon 1960a, b; Bacon *et al.*1971; Foot, 1974a, 1976c; 1979; Hoffmaster, 1959). In the early 80's in Tunisia, foliar insecticide applications with deltamethrin prior to harvest did not reduce tuberworm infestation (Von Arx *et al*. 1987b). In Israel, good control was achieved using Insect Growth Regulators (IGRs) in comparison to metamidophos applied at the lower part of the canopy (Berlinger 1992). In the U.S. Pacific Northwest, research has shown that applying insecticides at and after vine kill almost always reduced *P. operculella* damage in tubers (Rondon *et al.* 2007). As a reference, a list of products that have been found to be effective for control of *P. operculella* in Oregon and Washington can be found at http://insects.ippc. orst.edu/pnw/insects. This link is regularly updated. Application of insecticides to reduce tuber damage is a very important issue. Gubbaiah and Thontadarya (1977) observed that the moths were more active during evening hours; during sunny days moths were found hiding on the undersurface of leaves; thus application should be in coordination with peak in insect activity. Trials in 2005 in the Columbia Basin suggested that the application of three insecticides (esfenvalerate, methamidophos, and methomyl) beginning at different intervals before vine kill, significantly reduced tuber damage, but there was no advantage in beginning control efforts earlier (4 weeks prior to vine-kill) than later (1 week prior to vine-kill). This information was generated for potatoes that were chemically killed down.

Practices to be followed in fields that are allowed to slowly and naturally die down have not been adequately addressed but that situation poses a different question since tuber infestation could occur as the canopy opens slowly over a long time period (Rondon *et al*. 2007; Clough *et al*. 2008). Spraying chlorofenvinphos (0.4 kg a.i./ ha) acephate (0.5 kg 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 at 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); phoxim (Voiaton), fenitrothion, chlorpyriphos-methyl, malathion and phospha- midon reduced foliage infestation of PTM (EI-Sebae *et at.,* 1975). In Queensland rotenone dust is recommended for commercial use (Passlow and Rossiter, 1973). In field tests, in Egypt, 0.4% carbaryl gave the best control (Assem and El-Nahal, 1970). In India, 0.4% fenvalerate dust at 50 g/100 kg tubers was used to evaluate losses (Trivedi, 1990)

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 (Doutt, 1947; Watmough *et al*. 1973; Annecke and Mynhardt, 1974; Cardona and Oatman, 1975; Whiteside, 1980; Kfir, 1981a; Whiteside, 1981, 1985) along with Trichogramma (Flanders, 1935, 1945; Klomp and Teerink, 1962; Martson and Eartle, 1973; Lewis *et al.* 1976; Kfir, 1981b, 1983). In South America, *Copidosoma* and *Apanteles* wasps controlled *P. operculella* field populations (Redolfi and Vargas, 1983). In Australia, *A. subandinus* Blanchard, *Orgilus lepidus* Muesebeck and *Copidosoma desantisi Annecke* and *Mynhardt* (*C. koehleri sensus*) were reported in a 1979 survey. Other parasitoids like Tachinidae (*Incamyia cuzcensis* T.T. and *Lixophaga diatraeae* Towns), and more than 60 Hymenoptera (Braconidae, Encyrtidae, Eulophidae, Ichneumonidae, Mymaridae, Perilampidae, Pteromalidae, Scelionidae, and Trichogrammatidae) have also been described by several authors (Labeyrie 1959; Lloyd and Guido 1963; Jai Rao 1967; Rao 1967; Rao and Ramachandran-Nair 1967; Leong and Oatman 1968; Rao and Nagaraja 1968; Oatman et al. 1969; Lloyd 1972; Odebiyi and Oatman 1972; Cruickshank and Ahmed 1973; Callan 1974; Oatman et al. 1974; Oatman and Platner 1974; Cardona and Oatman 1975; Chundurwar 1977, 1978; Odebiyi and Oatman 1977; Mitchell 1978; Divakar and Pawar 1979; Franzman 1980; Sankaran and Girling 1980; Briese 1981; Flanders and Oatman 1982, 1987; Powers and Oatman 1984; Izhevskiy 1985; Horne 1990, 1993).

Among all parasitoids listed, there are some ecological differences; for instance, while *C. desantisi* oviposits in the eggs, *A. subandinus* and *O. lepidus* prefer young *P. operculella* larvae (Platner and Oatman, 1972a). In the U.S. Pacific Northwest, only two parasitoid wasp species have been collected from *P. operculella* although in small numbers: *Habrobracon gelechiae* and unidentified species OSAC # 21138 (Rondon *et al.* 2007). However, in some instances, parasitism and predation has been estimated at 40% and 79%, respectively (Coll *et al*. 2000). Level of parasitism was found higher in larvae feeding in the leaves (65%) as compared to larvae infesting tubers (32%) (Briese, 1981), suggesting that parasitoids find it easier to encounter the host in exposed potato leaves rather than on tubers buried in the ground. Callan (1974) unsuccessfully tried to correlate parasitism and field damage; he indicated that since parasitism does not lead to instant mortality, it cannot provide immediate control, therefore raising some questions regarding the efficacy of the use of natural enemies. The studies of the culturing and mass producing of parasitoids conducted since the early 1970's could potentially promote the increased use of natural enemies (Flanders 1930, Finney *et al*. 1944, Platner and Oatman 1968, 1972b). These and future studies will promote the benefits of using biological control either by artificial releases (i.e. inundative or inoculative) or conservation of natural enemies that can be used in combination with chemical control. In India, several parasitoids, predators and pathogens were recorded (Ramakrishna Ayyar, 1928; Uilah, 1939, 1941; Usman, 1957; Dalaya and Talgeri, 1971; Ramchander Nair and Rao, 1972; Amonkar *et al*, 1979). 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* app., *PrIstomerus vulnergator* and *Bracon* sp. were the most abundant, causing 4-17% parasitism under field conditions (Ramachander Nair and Rao, 1972). Two parasitolds, *Nythobla* sp. and *Chelonus curvImaculatus* were found to give good control In Pretoria (Watmough *et al.*, 1973). *Dladigma niolliplum* caused 2.5-5.0% parasitization 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. *Copidosomaa koehleri*, an egg and larval parasitoid gave 28-61% parasitazation in Maharashtra (Dalaya and Patill, 1973). Continuous release of these parasitoids was required for effective suppression of PTM (Khandge *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). *Baculovirus* and *Bacillus thuringiensis* var, Kurstaki were also found to protect tubers for up to 60 days (Amonkar *et al*., 1979)

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 (Reed 1969, 1971; Reed and Springett 1971; Hunter 1973; Briese and Mende 1983; Alcázar *et al*. 1992; BenSalah and Aalbu 1992; Das *et al*. 1992; Raman 1994; Kroschel *et al*. 1996b; Lery *et al*. 1997; Roux and Baumgartner 1998; Setiawati *et al*. 1999). 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 (Lacey and Arthurs, 2005; Arthurs *et al*. 2008). 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). Little information has been reported on the activity of the *P. operculella* granulovirus (PoGV) in vivo (Hunter *et al*. 1975) or the history of the spread of the virus.

Nevertheless, it seems that the granulovirus (GV) accompanied the tuber worm from its South America center of origin. The name of the virus derived from its granular appearance consisting on a single viral rod which enters *P. operculella* body by ingestion and from there it reproduces causing the death of the insect. A comprehensive study of this process was discussed by Reed (1971) in the early 70's and later by Sudeep *et al*. (2005). It is interesting that this GV, first isolated in the mid 1900's from a laboratory *P. operculella* population, was not reported to occur naturally in the field before the early 40's and 60's (Steinhaus 1945; Reed 1969, 1971; Reed and Springett 1971). In 1979, Foot reported two larval pathogens in field populations of *P. operculella*, including a GV virus and an unidentified bacterial disease (Foot, 1979). In South Africa field populations of *P. operculella* were found infected with GV (Broodryk and Pretorius, 1974). By the late 80's and early 90's GV was widely tested in the field. Ben Salah and Aalbu (1992) recommended the application of GV-water spray 2 weeks prior to harvest rather than GV-powder application since it was easier to apply as a water solution than as a powder. Results of the use of viruses in the field has been variable: close to 100% control was achieved in Western Australia (Reed and Springett, 1971) while 53 to 85% infection rate was achieved using the same dosage in a similar location (Matthiessen *et al.* 1978). In this situation, weather conditions probably played an important role in the success of the use of the viruses although it was not thoroughly discussed by Reed and Springett or Matthiessen. Another explanation for this discrepancy may be the difference in susceptibility or the potential development of resistance to a GV strain between fields populations occurred in *P. operculella* Australia population. Timing of virus application (Briese, 1981; Briese and Mende, 1981,Reed 1971; Reed and Springett 1971), methods of application, concentration and ultraviolet radiation can influence effectiveness of control (Kroschel et al. 1996a, b; Sporleder et al. 2001, 2005; Sporleder 2003). The only bacterium evaluated to control *P. operculella* has been *Bacillus thuringensis* Berliner (*B. thuringensis*). This is a naturally occurring bacterium that produces crystal toxins (Beegle and Yamamoto, 1992; Lacey *et al*. 2001) which cause lysis of the midgut epithelium. Two crystal proteins, Cry1A and Cry1B have been isolated under laboratory conditions and isolated from several subspecies including kurstaki, thuringensis, tolworthi, galleriae, kenyae and aizawai

(Salama *et al*. 1995a, b). The lethal concentration (LC_{50}) varies according to subspecies and application method (i.e. dust versus liquid formulations) (Amonkar *et al*. 1979; Hamilton and Macdonald, 1990; Von Arx and Gebhardt, 1990). Although commercial mixtures of Bt are being used successfully to control lepidopteran larvae (Harpaz and Wysoki, 1984), its current use is primarily on small field organic farms (Broza and Sneh, 1994), in laboratories and storage facilities. Repeated pre-harvest applications are required because Bt is degraded by ultraviolet light and rain (Awate and Naik, 1979; Broza and Sneh, 1994; Salama *et al*. 1995b). Also, post-harvest applications in non-refrigerated stored potatoes may be needed (Von Arx *et al*. 1987a; Salama *et al*. 1995a; Kroschel and Koch, 1996; Farrag, 1998). *A granulosis* virus which is pathogenic and specific to PTM larvae has been isolated in India (Amonkar *et. al*., 1979). In field evaluations, it has been found to be as effective as insecticides in preventing tuber damage lasts for about 12 weeks.

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 of larval 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 (Hafez *et al*. 1997; Sewify *et al*. 2000; Worapong *et al*. 2001; Stinsen *et al*. 2003; Lacey and Arthurs, 2005; Mercier and Smilanick, 2005). Seed extracts of *Oclmum bacillicum*, rhizomes of *Acorus calamus* and leaves of *Ageratum conyzoides* havebeen 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* have also 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 soapnut 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). Resistance to PTM was studied by Raman and Palacious (1982) who reported 22 primitive and 21 wild potato cultivar accessions as highly resistant to PTM out of 3747 primitive cultivars and 452 wild species screened. Cultivar Red was resistant while K. Shakti, QB/A16-43 and VB/A92 were tolerant. Bhalla and Chandla (1986) also examined PTM resistance. The release of sterile males in the ratio of 10:1 (sterile: normal) was found to reduce PTM populations by 82.5% within two generations in store in India (Rahafkar *et al.*, 1975). Isolation of the sex-pheromone in California by Foudu *at al.* (1975) and Bacon *et al.* (1976) concluded that two mixtures of trans-4,cis-7-trideoadien-1-01-acetate (PTM1) and PTM 1 + *trans-4,c/s-7,cis-10-tridecatrien-1-01* acetate (PTM2) were most effective for monitoring and mass trapping PTM (Saxena *et al.*, 1982; Raman, 1982, 1984; Trivedi, 1989).

Parasitoids, predators, and pathogens can control *P. operculella* populations effectively under low input and conventional production systems if chemicals compatible with the biological control agents are chosen. As sustainable agricultural practices become more widely adopted, natural enemy communities will become increasingly on demand. Therefore, understanding the basis of natural interactions is an important step towards long-term balanced agroecosystem management. Other novel ways to control *P. operculella* include the use of the inherited sterility technique. This technique has been suggested as an alternative control method to suppress *P. operculella* populations (Makee and Saour, 1997; Saour and Makee, 1997; Makee and Saour, 1999). The results, unfortunately, have been mixed. The use of gamma radiation applied to fully developed *P. operculella* pupae affected their reproductive potential and their behavior (Elbadry, 1964); those effects are undesirable under the basic premise of the "sterile technique" (Knipling, 1955) since this technique is a method of biological control, whereby millions of sterile insects are released. Insects released are normally male. The sterile males will compete with the wild males for female insects; if female mates with a sterile male then it will have no offspring reducing the next generation's population.

Loss in Storage: Potatoes should be stored at temperatures ranging between 7.2 to 10°C (University-California, 2006). Since *P. operculella* does not develop at temperature below 5°C (Al-Ali *et al*. 1975), it should not cause economic problems in cold storage (Roux *et al*. 1992; Keasar *et al*. 2005). In theory, it might be possible for the tuber worm 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, 1934). In developing countries, potatoes are stored in sheds, under trees or in uncooled warehouses (Hossain *et al.* 1994; Keasar *et al.* 2005). Tuber worm damage under those conditions can be devastating (up to 100% in some cases). Exposed tubers in the field serve as the primary source of infestation during storage (Gubbaiah and Thontadarya, 1975). In developing countries, the majorities of potato farmers were piles the tubers in storage and cover them with potato vines which were infested with larvae in the field, and can then infest the stored tubers in storage (Gubbaiah and

Thontadarya, 1975). Well ventilated storage rooms that can be cooled through water evaporation plus the installation of insect nets should be added when possible to reduce storage problems (Ilangantileke *et al*. 1997). In North Africa, the rapid increase in population of *P. operculella* in the field prior to harvest results in heavy infestation during storage (Essamet *et al*. 1988; von Arx *et al*. 1988; BenSalah and Aalbu, 1992; Salah *et al*. 1994; Laarif *et al*. 2003). Tubers stored for seed can be treated with pyrethroids and organophosphates in certain cases (Islam *et al.* 1990; Das *et al*. 1992; Hossain *et al*. 1994; Hanafi 1999; Keasar *et al*. 2005), although the practice can be illegal and life threatening when used inappropriately. Under rustic storage conditions in the Philippines, granulo-viruses (GV) at 5 kg · ton-1 of tubers has been effective for up to 2 months of storage; treatment combinations of GV + Bt + deltametrhin + Lantana or deltamehtrin + Bt + GV yielded zero to low pest infestation; Bt alone was ineffective (Das et al. 1992). 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 Minthostachys, both in dried and powdered forms were effective in controlling *P. operculella* (Raman *et al*. 1987).

Role of Resistance: Reducing *P. operculella* damage through cultivar selection appears possible. The evaluation of potato germplasm for resistance to potato tuberworm is valuable to developing integrated tuberworm management (Horgan *et al.* 2007); however, no fully recognized resistance cultivar has been bred to date. Few attempts have been made to identify plant cultivars resistant to tuberworm (Foot, 1976a; Raman and Palacios, 1982; Musmeci *et al.* 1997; Arnone *et al*. 1998; Musmeci *et al*. 2005). In the late 70's, 20 cultivars were compared for foliar and tuber resistance with negative results (Foot, 1976a). In the 80's, the International Potato Center tested 3,747 and 452 germplasm of primitive and wild potato species, respectively, from which 22 primitive and 21 wild germplasm were found resistant (Raman and Palacios, 1982). In 2009, 13 germplasm were used for tuber resistance studies (Rondon *et al*. 2009). These germplasm were: A0008TE, A97066LB, NY123, PA00N10-5, PA99N2, PA99N82, Paciencia, Q174-2, Russet Burbank, Rubi, Ranger Russet, Spunta G2 (Cry1IA1= Cry5), and T88-4. Tuber resistance of potato germplasm was determined based on the number of mines per tuber and the number of live larvae. Tubers of the transgenic clone Spunta G2 (Douches *et al*. 2002) were resistant to tuberworm damage. All other germplasm tested in this study, including Russet Burbank and Ranger Russet, were susceptible to tuberworm in the field and laboratory experiments. Other host resistance studies have shown that there are independent resistance mechanisms in the foliage and tubers (Brown, 2006). Malakar and Tingey (1999) found limited foliage resistance of Solanum berthaultii (Hawkes) to *P. operculella*, while Musmeci *et al.* (1997) found some foliar resistance on wild potatoes and interspecific hybrids. Little information is known regarding the effect of either leaf or tuber resistance on the biology and ecology of potato tuberworm (Malakar and Tingey, 1999). A combination of partially resistant germplasm to P. operculella and appropriate management practices could answer the "**zero" tolerance required by the potato industry** (Rondon *et al.* 2009). The development of resistant varieties could mark a new era in the management of PTM.

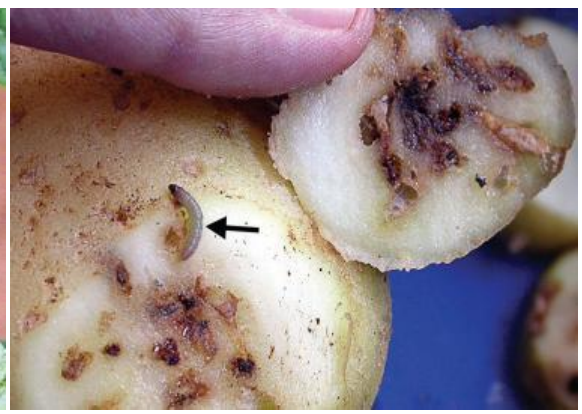
Control of Potato tuber moth with CIPC in country stores: Control of PTM has been achived @ 1-2 ml/liter of water and then sprayed @ 40 ml / tone dose on the tubers. Tubers need drying before storage to avoied rottage due to excessive moisture.Stores with treated tubers are kept closed for 1-2 days after treatment for allowing CIPC to settle down on the tuber surface. For fogging, 35-40 ml of CIPC (Oorja solution) ios required for treating one tone of potatoes, similar to that recommended for sprout suppression. The sprouting was also reduced to the level of 3.7-5.8 per cent by CIPC application as against 72.5-80.0 per cent in untreated tubers during storage for 50 days under country stores. Further, the experiment counducted for two rears under country store of Kangra valley with CIPC spray application of 30 EC chemical gave almost complete control of PTM for up two months in store becides suppressing sprout growth. There was negligible PTM incidence (0.3-2.8 per cent) in CIPC treated tubers compared to 3.6-27.6 per cent incidence in untreated tubers kept under country stores. The degree of infestation was slight (<3 feeding holes/tuber) in CPIC treated tubers having PTM infestation, wereas it was medium (3-4 holes) to serve (< 4 holes) in untreated tubers losts. CIPC treated tubers appered healthy and unshrivelled apperarance. From inside also, the treated tubers was undamaged , through, the control tubers showed galleries formed due to PTM infestation, thereby resulting in unacceptable tubers quality CIPC cannot be used on fresh potatoes immediately after harvest. During harvesting, there is considerable amount of potato bruising and the skin in not fully formed at this stage. The treated stores have to be kept closed for 24-48 hours, so that CIPC may be deposited on the tubers. The maximum permissible limit for CIPC residuce is in table potatos in 30 mg/kg of tubers. In the samples collected from treated stores, the residuce were always found within the permissible limit. The residuce concentration were 7-8 mg/kg in pells and 0.2-0.8

mg/kg in peeled tubers immediately after treatment and reduced to the concentration of 0.5-4 mg/kg in peels and 0.1-0.3 mg/kg in peeled tubers after 50 days of treatment. Therefore, the treated potatoes where found to be safe for consumption (Chandla *et. al*., 2008).

Conclusions The potato crop is one of the world's most important food crops, along with rice, wheat, and maize (Ross 1986; Douches *et al*., 2004). Potatoes are widely grown over many latitudes and elevations. Especially in developing countries, potato production is important for subsistence and for adding nutritional balance (Douches *et al*., 2004; Navarre *et al.*,2009). Unfortunately, severe losses can occur in storage, especially in developing countries where low income farmers cannot afford refrigerated storages. Increasing potato production in a sustainable manner while protecting producers, consumers, and the environment will requires an integrated approach. Combating pests such as *P. operculella*, a devastating worldwide pest of potatoes, is a continuous challenge that growers must face as they intensify their production techniques to satisfy the increasing demands of the international market. A thorough knowledge of the distribution, host range, , ecology and economic effect of a pest is necessary before developing management practices. It is difficult to achieve effective control by a single method when the infestation is very high. When populations are low, any individual component may be effective. Other actions such as the collection of left-over tubers from the field, planting 6 cm deep, the use of healthy seed material, frequent irrigation to reduce soil cracks, covering of exposed tubers, release of parasitoids in the early stage of the crop should be practised. In later stages, the selective use of recommended insecticides and mass trapping with sex pheromones should be put into practice (Trivedi and Rajagopai, 1988). In storage, it is necessary to remove damaged tubers before storing: Sex pheromones may be used for monitoring and mass trapping with water traps. Screening of germplasm may be practised In endemic areas to identify resistance in the field and in storage. This will provide a base for long-term management to reduce the pest incidence in a continuous cropping system.

Acknowledgments The author gratefully acknowledges Drs. SK Chakrabarti, Ex Director and Manoj Kumar, Joint Director (acting) for their encouragement.

POTATO MOTH LIFECYCLE STAGES AND SYMPTOMS OF DAMAGE



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