Ecological Approaches to Integrated Pest Management of the Potato Tuber Moth, *Phthorimaea operculella* Zeller (Lepidoptera, Gelechidae)

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Introduction

The potato (Solanum tuberosum L.) is grown in over 140 countries, more than 100 of them in the tropics and subtropics. Potato is nutritious and highly productive, but losses through pests and diseases during the cropping period and storage are high. Oerke et al. (1994) estimated the total loss from diseases, pests and weeds in potato at 41.3%, with losses from diseases and pests 16.3 and 16.1%. To keep losses from pests down, pesticide inputs are often extremely high, amounting up to US$ 800-1000 ha-1. In tropical and subtropical agroecosystems, the potato tuber moth (PTM) (Phthorimaea operculella) is considered the most damaging potato pest. Larvae mine both leaves and tubers, in the field and in the store, making the pest difficult to control. Over the years, farmers have responded with a unilateral use of insecticides applied in the field and store to control this pest and calendar sprayings of DDT or other substances including pyrethroids. This practice has caused a rapid build up in the resistance of PTM (Richardson and Rose 1967; Cisneros 1984). The serious health threats of chemical pesticides to farmers, consumers and the environment has increased interest in the search for safer control alternatives through the development of Integrated Pest Management (IPM). This approach has been shown to successfully control this pest, thereby reducing or avoiding the use of insecticides (Kroschel 1995, Lagnaoui et al. 1995, Palacios and Cisneros 1997). Ecological approaches to IPM for PTM are based on an overall understanding of pest population dynamics supported by phenology modeling, yield loss assessments and the use of control thresholds for minimizing insecticide applications, habitat management and biological control, and special consideration for storage management. In this paper, we summarize results and experiences gathered in the Andes of Peru, in Egypt, and in the Republic of Yemen.

Distribution

The potato tuber moth (PTM, also referred as to potato tuberworm), which probably originated in the tropical mountainous regions of South America (Graf 1917), has become a cosmopolitan pest of potato and other solanaceous crops like tomato (Lycopersicon esculentum Mill.), tobacco (Nicotiana tabacum L.) and aubergine (Solanum melogena L.). In addition, wild species of the family Solanaceae, including important weeds in potato (e.g. black nightshade, Solanum nigrum L.) serve as host plants. Today, its distribution is reported in more than 90 countries worldwide (Fig. 1). The moth occurs in almost all tropical and subtropical potato production systems in Africa, Asia and Central and South America. While it still can be of economic significance in subtropical regions of southern Europe, the long, cold winters in temperate regions generally restrict its development and reduce its pest status.

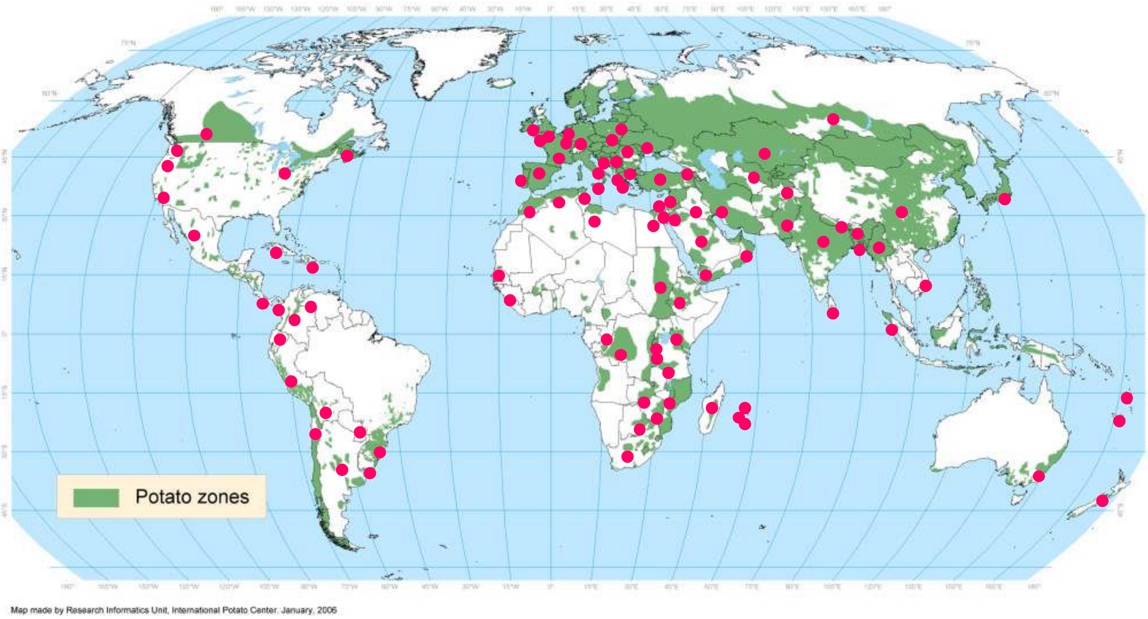

Figure 1. Distribution of the potato tuber moth: Points indicate zones where PTM has been reported.

Population dynamics of PTM as affected by abiotic factors

After winters or longer non-cropping periods, moths surviving in the open, mainly on left-over potatoes, are the initial population at the start of a potato season. In smallholder production systems where saved, instead of improved certified seed, is used PTM infested seed contribute substantially to a rapid population build up, as demonstrated in the Republic of Yemen (Kroschel and Koch 1994, Kroschel 1994). In such situations early potato cropping with non-infested healthy seed reduces the risks of a PTM infestation. Temperature is the main driving factor for PTM development, with mean temperatures of more than 18ºC being most favorable for population build-up and high infestation. Mean temperatures of more than 21ºC lead to development times of less than 30 days to complete one-generation cycle (Kroschel & Koch 1994). In addition to the overall effect of temperature, investigations in different agro-ecological zones have shown that precipitation also influences PTM development. Leaf infestation becomes highest when potato is cultivated during warm dry seasons, especially under furrow irrigation where leaf infestation can reach up to 35 mines/ plant (e.g. Republic of Yemen) (Kroschel 1995). In contrast, heavy rains or regular sprinkler irrigation influences the flight activity of adults and limits infestation. In rain-fed potato in the Andean highlands (e.g. Rio Mantaro Valley, Peru) with an annual precipitation of more than 700 mm, leaf infestation is low but delaying harvest during the dry season increases tuber infestation tremendously. In addition, the availability of food might also affect PTM populations. Although the temperature is favorable for PTM development in Egypt during summer, from June to October the population declines significantly since potato is not cultivated (Keller 2003).

Modeling of PTM phenology and mapping its distribution potential using GIS

To get an overall understanding on how temperature affects PTM in different agro-ecologies a temperature-based population model was developed (Sporleder et al. 2004), integrating development, mortality of immature life stages, and reproduction at constant temperatures ranging from 10 to 32ºC. Theoretical development thresholds of 11, 13.5 and 11.8ºC were calculated requiring incubation times of 65.3, 165.1 and 107.6 degree-days for the egg, larval, Based on min. and max. temperatures the model predicts the pest population growth potentials, i.e. life-table parameters (intrinsic rate of increase, net reproductive rate, number of generations per year and average generation time, development time for all life stages, etc.), for any potato cropping area. Recently, we linked the model to a geographical information system (GIS) to produce maps that visualize the PTM worldwide and regional distribution potential in potato-cropping areas (Fig. 2).

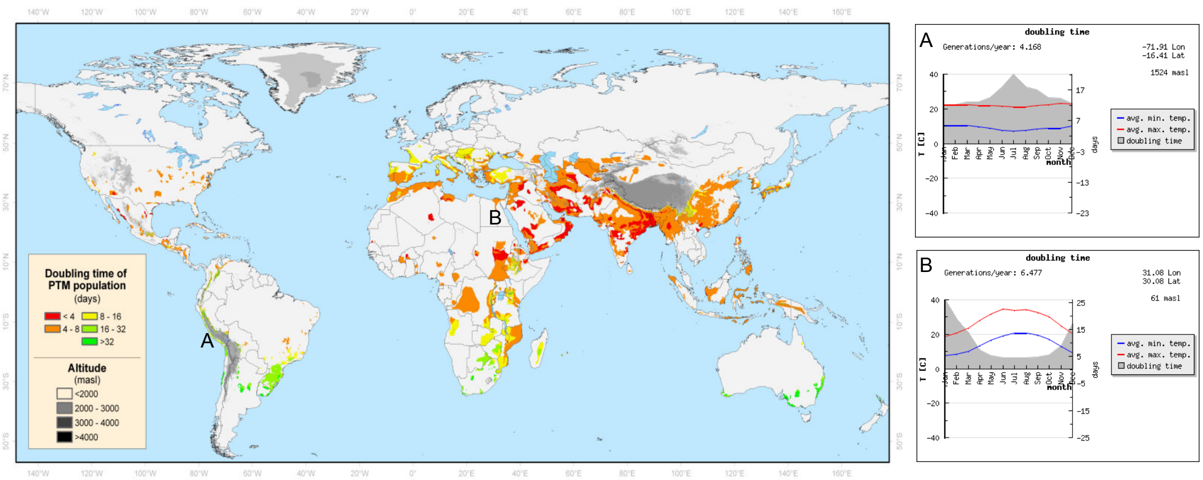

Figure 2. The population growth potential of PTM, here expressed as population doubling time (*Dt*), simulated for all potato-growing areas in the month of June worldwide (zones where temperature conditions do not favor population growth during the year for more than 2 months were previously excluded). Small diagrams show the growth potential of PTM during the year for selected locations (A. Arequipa, Peru; B. Cairo, Egypt) as examples.

In subtropical regions the moth may produce over nine overlapping generations per year, i.e. all developmental stages can be found continuously in potato fields. Generally it was found that PTM development is limited by the 10 °C annual isotherm in both the southern and northern hemisphere. However, a recent outbreak of PTM in the Columbia Basin showed its ability to become a pest in temperate regions. Modeling showed that in this region 2-3 PTM generations can potentially develop per year. However, due to slower PTM development, developmental stages would be more separated than in warmer regions and the highest population increase would take place only during the potato vegetation period (July-August). The high estimated mortalities mainly of egg and larval stages, which occur in cold winters with longer frost spells, suggest that substantial PTM numbers might only survive during mild winters to endanger the potato crop in the following season. Building up an early warning system by monitoring the pest flight activity through pheromone traps could forecast the probability of a seasonal-dependent PTM problem, in order to prepare farmers to subsequently monitor PTM field infestation development.

Yield loss assessment and development of control thresholds

Field experiments to evaluate the effect of PTM leaf and stem mining on tuber yield showed that only high infestations early in the season directly affect tuber yield. In the Republic of Yemen with 35 mines/plant at growth stage 50, tuber yields were reduced by 25% (Kroschel 1995). In comparison, 9 mines/plant at growth stage 70 did not significantly affect tuber yield in Egypt (Keller 2003).

However, the strong correlation established between leaf and consequent tuber infestation suggests that reducing the PTM population density during the growing period is the key to reduce tuber infestation at harvest. Preliminary field experiments with only one insecticide application at growth stage 70 instead of three seasonal applications have not proved sufficiently effective in reducing tuber infestation; but investigations should continue to develop this option of control.

Since PTM occurrence and infestation dynamics might vary from field to field and region-to-region, the use of a control threshold and a monitoring system would be ideal to predict the necessity and right time for PTM control. A control threshold is defined as that level of infestation at which a control measure must be implemented in order to prevent the pest population from exceeding the economic threshold (i.e. costs of control are equal to the value of the crop loss). For determining a control threshold, data and information are required on the relationship between pest population incidence and the percentage crop loss, the potential crop yield without any pest infestation, the prices of the harvest produce and the costs and efficacy of a given control measure. For the Republic of Yemen a control threshold of one-mine/two potato plants at growth stage 20-30 has been determined and for its practical application a sequential sampling procedure developed to monitor leaf infestation (Kroschel 1995). Control thresholds are often the weakest component in IPM since many factors are uncertain (differences in potato varieties, variable prices) requiring its adjustment to different regions prior to its use. Low leaf infestations, e.g. in Egypt or in the Andes, do not suggest applying rigorously the concept of a control threshold but monitoring the PTM leaf infestation would be a valuable decision tool for any field control prior to harvest aiming at reducing tuber infestation. Pheromone trap catches only indicate PTM flight activity and do not reflect the infestation in individual potato fields. Their use as a decision tool is therefore not applicable. In addition to the population build up of a moth population during potato growing, various cultural practices have been shown to influence damage of potato tubers at harvest, with hilling up, use of sprinkler irrigation and harvest time as the most important ones. Also, in loamy soils, PTM gets much easier access to tubers through soil cracking than in sandy soils. Finally, those specific conditions have to be taken into consideration for establishing adequate field control.

Habitat management and promotion of beneficial insects

Maintaining and promoting the natural antagonistic potential is a major element of IPM. This stabilizes the agroecosystem and can reduce the incidence of pests. For controlling potato pests, a large number of entomophagous species of the families Aphidiidae, Syrphidae, Aphidoletes, Carabidae, Coccinellidae and Chrysopidae are important natural limiting factors (Hassan 1989) that could be promoted either through habitat management or reduced and selective use of insecticides. Since potato is often a pesticide-intensive crop, little information is available about the impact and natural control of potato pests and their relation to the natural habitat. In the Rio Mantaro Valley, Peru, where several beneficial insect predators and parasitoids have been described for potato, occurrence is very low due to the use of broad-spectrum insecticides such as organic phosphorous compounds, carbamates and synthetic pyrethroids (Keller 2003). Non-selective insecticides harm beneficial insects either directly through the application but also indirectly through spraying deposits on leaves. Further insecticides can have a repellent effect, reduce longevity and fertility as well as cause changes in the synchronization between predators/parasitoids and their prey, leading to a reduced overall efficacy of beneficial insects. During potato production in the Republic of Yemen, with little or no use of insecticides, we had some good indications that due to a large number of predators (25) and several parasitoids, the agro-ecosystem functions in a self-regulating manner, keeping pests like the green peach aphid (*Myzus persicaea* Sulz.), the potato aphid (*Macrosiphum euphorbiae* Thomas) or cutworms (*Agrotis segetum* Hfn.) under the control threshold (Kroschel 1995). In this system, small patches of cultivated fields alternate with fallow and non-agricultural land, edged by irrigation ditches and grass borders supporting a rich flora of flowering plants. These are important habitats and food sources for beneficial insects. Additionally, diversification is often enriched through minimal weed control throughout potato cropping. Numerous surveys have shown that pests are rarer in rich diversified agroecosystems where weeds are present, compared to weed-free crops (Risch *et al*. 1983; Altieri 1987, 1988). Beneficial insects require pollen and nectar during at least one stage of their development (Moltan and Rupert 1988). For adults of several insect groups, weeds are important food sources and measures that increase plant diversity in agroecosystems – either around or within fields – support the increase in the number and abundance of beneficial insects. This fact has called for the development of a “field border program” in Germany to promote the establishment of a weed community around field borders through non-herbicide applications. Further, the strip cultivation or the use of soil cover plants in perennial crops using plants of the families Asteraceae, Brassicaceae or Apiaceae, or the traditional mixed cropping systems in the Tropics, are possibilities to promote self-regulatory processes in agroecosystems. In Yemen, PTM was found to be the only pest that justifies control due to prevailing climatic factors that are optimal for PTM development (eight generations per year), and the local farming practices of using infested seed that encourage PTM development after the non-cropping (winter) period. However, its occurrence and damage was also substantially controlled by the parasitic ichneumon wasp *Diadegma molliplum* Holmgren and the braconid *Chelonus phthorimaea* Gahan that reached total parasitization rates of more than 80% at the beginning of the second potato crop (Kroschel and Koch 1994). A rich supply of nutrients enables parasitic Hymenoptera to find and parasitize more hosts over a longer period of time and with an increased reproductive capacity. Finally, to fully understand and exploit the potential of habitat management for the promotion and natural conservation of beneficial insects, more in-depth ecological studies are needed in potato production systems to develop practical recommendations for IPM.

Biological control

Biological control of PTM refers to the active use of beneficial insects (parasitoids) and/or microorganisms (pathogens: granulovirus, Bacillus thuringiensis) in biocontrol programs. Two approaches for the control of the potato tuber moth can be distinguished. First, the classical or inoculative biological control consists of the introduction and release of potential exotic antagonists for durable naturalization in those regions, where PTM has been unintentionally introduced and not co-evolved with specific and effective natural enemies to limit the pest infestation and tuber damage. Secondly, there is the inundative or bioinsecticide approach, in which endemic as well as exotic pathogens are mass-produced and applied periodically. Among 18 different parasitoids used for classical biological control species of the family Braconidae, including *Apantales subandinus* Blanch., *Orgilus lepidus* Mues., as well as *Copidosoma koehleri* Blanch. from the family Encyrtidae have been most successfully established in several countries. However, the control effects were inconsistent in different regions. In Zimbabwe, releases have been so successful that PTM was eliminated as a significant potato pest (Mitchell 1978).

In South Africa, releases resulted in displacement of native species but total parasitization was not sufficient to keep PTM populations below the damage threshold. In Australia, overall parasitization rates of 80% at the end of the growing season due to releases of *A. subandinus*, *O. lepidus* and *C. koehleri* were not sufficient for adequate control of PTM. However, Horne (1990) pointed out that in areas where no chemical insecticides are used, the parasitoids have become a very important factor limiting PTM, although an integrated control program would be required to further increase their effectiveness. PTM has spread into many areas (Africa, e.g. Tanzania, and Asia, e.g. Nepal, Bhutan, Indonesia), where classical biocontrol could be applied to support the sustainable management of this potato pest.

Given the controversy concerning the use of chemical insecticides, biopesticides based on specific microorganisms (entomopathogens), i.e. the endemic granulovirus infecting *P. operculella* (*Po*GV, Baculoviridae) and *Bacillus thuringiensis*, have become an integral part of IPM approaches for PTM in several developing countries. These entomopathogens have proved to be very effective to protect stored potatoes and may also replace the application of chemical insecticides to growing potatoes. The advantage of Baculoviruses is that they replicate in their hosts and persist in the environment due to horizontal and vertical transmission, which may cause long-term suppression of pest populations. *Po*GV was first isolated in the late 1960s in Sri Lanka and propagated in Australia (Reed 1969). Later *Po*GV was isolated in various parts of the world (Broodryk and Pretorius 1974, Raman and Alcázar 1990, Kroschel 1995). High natural infection rates are commonly observed in PTM field populations; e.g. mean natural infection rates of 11% were determined in the Republic of Yemen (Kroschel 1995). The first large-scale field trials using the virus as a selective biological insecticide in potato fields in Australia were very promising (Reed and Springett 1971, Matthiessen et al. 1978). Single, early applications of the virus resulted in sufficient control and also in an extensive spread of the virus to untreated areas. Kroschel *et al.* (1996b) found that a dose of 5×10^{13} granules/ha of *Po*GV, applied twice during the vegetation period in potato fields successfully suppressed the host population, similar to the application of chemical insecticides. These *Po*GV applications resulted in a large production of secondary inoculum; around 70% of the fourth-instar larvae collected 19 days after applications were infected and the virus had spread to neighboring potato fields. However, the impact of secondary inoculums of *Po*GV and the beneficial role of the soil as an important reservoir of the virus on subsequent PTM generations has not yet been studied in detail. A considerable impact may be expected, because *Po*GV applications to the soil surface before harvest reduced tuber infestation at harvest by 73%, and subsequent in-store infestation failed to develop (Ben Salah and Aalbu 1992).

One of the main constraints using *Po*GV in the field is its rapid inactivation due to solar (ultraviolet, UV) radiation. Kroschel *et al*. (1996a) determined half-life times of 1.3 days for *Po*GV. Recent experiments indicated that *Po*GV degradation does not follow a simple exponential curve. Depending on radiation energy, initial inactivation can be very fast, with half-life times of 0.25-0.3 days, but the inactivation curve was curtailed when about 90-95% of the viruses were inactivated, showing increased half-life times of about 2.3 to 2.8 days. Therefore, a certain portion of virus particles remain active for long periods of time after application and may contribute to long-term suppression of the pest and further dissemination of the pathogen. Several efforts were made to protect the virus through formulation and ultraviolet adjuvants (Sporleder 2003). Selective adsorbents (dyes) had no significant effect on *Po*GV stability.

Table 1. Effects of several UV adjuvants on PoGV activity and UV-stability (source Sporleder 2003).

UV adjuvants	**Effect on *Po*GV activity (LC_{50})**	**Effect on *Po*GV stability ($t_{½}$)**
Selective absorbents (dyes)		
Congo Red	reduced activity	no effect
Folic acid	neutral	no effect
UVITEX	increased variability	no sig. effect
Optical brighteners		
Tinopal	increased activity (8-134 fold)	no effect
Antioxidants (free radical scavengers)		
Propyl gallate	not clear	~3-fold increased
Phenylthiocarbamide	~5-fold increased	~2-fold increased
Ascorbic acid	neutral	~0-2-fold increased
Peroxidase	neutral	~2-fold increased
Superoxide dismutase	neutral	~6- fold increased
Host derived material		
Macerated larvae	-	~6-fold increased

Optical brighteners (Tinopal) increased viral activity 8 to 134-fold but did not increase viral stability. Several antioxidants, which act as free radical scavengers, increased virus stability 2 to 3-fold without influencing virus activity. However, *Po*GV in host-derived material (macerated larvae) were best protected against radiation (approximately 6-fold increased stability compared to purified *Po*GV) (Table 1). Apart from the ultraviolet-inactivation, other aspects need to be considered to optimize field use of PoGV. Baculoviruses attack only certain stages of their host, in particular the larval stage, while susceptibility to the virus decreases with larval age. Therefore, PoGV applications must be directed against neonate and very young larvae, as well as against the eggs (emerging L1-larvae may take up a lethal dose with consumption of the egg chorion as long as the virus was deposited on the egg surface). Knowledge of the stable age structure of P. operculella is necessary to estimate the effect of a virus application on the population size of P. operculella. The phenology model developed for PTM may be used to estimate the stable age structure of PTM according to temperature data and to estimate the effect of a virus application on the population development.

Knowledge of the relationship between pathogen concentration (or dose) and the host response (mortality) is essential for giving recommendations for field applications. The slope of the Probit-regression is especially important for economic determination and optimization of field dosages and the interpretation of field responses. The slope for *Po*GV and its host *P. operculella* derived from field and laboratory experiments varies around 0.65 (Sporleder 2003). In contrast to chemical insecticides, which show steeper slopes in dose-effect relationships, *Po*GV applications of doses causing over 95% mortality in the field are probably not economically feasible. For example an application of *Po*GV at a dose of 5×10^{13} granules/ha in 500liters of water (10^{8} granules/ml) as used by Kroschel *et al.* (1996b) corresponds with approximately 10,000 virus-infected larvae/ha (1 larva equivalent LE ≈ 5×10^{9} granules.) Using Probit-regression curves derived from subsequent field experiments that dose would result in approximately 85% mortality of neonate *P. operculella* larvae. In order to increase the efficacy of the application to 95% or even 99% mortality a 10-fold and a 100-fold increase of the dosage would be necessary, respectively. On the other hand, 10 or 100-fold reduced rates would still result in 64% and 38% mortalities.

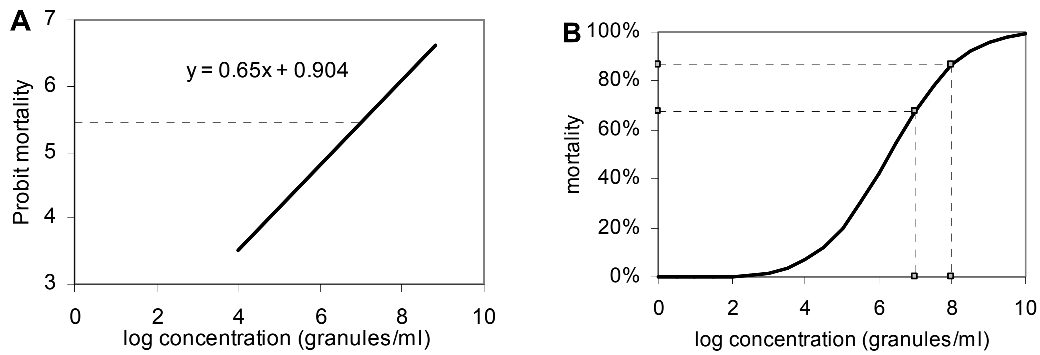

Figure 3. Concentration-mortality relationship between *Po*GV and its host *P. operculella* (neonate larvae); (A) shows the Probit regression line with an average slope of 0.65 derived from several leaf-disc assays, and in (B) probit mortalities are retransformed into percentage mortalities. In (B) it is illustrated that for increasing mortality responses from approximately 65% to appr. 85% a ten-fold increase of the *Po*GV concentration is necessary. For economic adjustment of field rates it may be beneficial to apply *Po*GV in several intervals at lower rates instead of targeting highest mortalities with one single application.

This gives options to use *Po*GV as a relatively inexpensive partial suppression agent in potato fields through the use of low dosages per hectare. In such an approach the virus should be applied at short intervals, depending on the pest population growth potential in different agroecological zones. Specific treatment thresholds for such an approach still need to be determined.

Storage control

After harvest, tuber infestation by first instar larva can be hardly noticed so that even with precautionary measures infested tubers are transferred to potato stores where further propagation of the pest and infestation of the whole stock takes place. In the absence of refrigerated stores, the damage to potatoes in rustic potato stores can be total within a few months if the tubers are left untreated. Both *Phthorimaea operculella* granulovirus (*Po*GV) and *Bacillus thuringiensis* var. *kurstaki* (*Btk*), depending on its availability, can be recommended to protect stored potatoes. Currently, *Po*GV is produced in Peru, Bolivia, Egypt and Tunisia using low cost facilities for propagation. A dust formulation, produced by selecting and grinding virus-infected larvae mixed with ordinary talc, has been used at the rate of five kilograms per tonne of stored potatoes (20 infected larvae per kilogram talcum). Research showed that the granulovirus reduces damage in stores by 91 and 78%, 30 and 60 days after application (Raman & Alcázar 1990). *Btk* mixed with fine sand dust containing quartz also provided effective storage control in the Republic of Yemen (Kroschel and Koch 1996).

A very low proportion, 40 g *Btk* mixed with 960 g sand, applied to one tonne of stored potatoes proved to be efficient. Further, natural insecticides prepared by water extracts of *Azadirachta indica* A. Juss. seed showed relative high levels of protection. The foliage of some plants, such as *Eucalyptus* sp., *Lantana camara* L., and the native species *Schinus molle* L. and *Minthostachys* sp. in the Andean region, have some repellent effects and can be recommended as additional, complementary control treatments. However, for effective management of PTM in rustic stores, storage hygiene is very important, i.e. cleaning floors, walls and ceiling of stores to destroy pupae and other life stages of the moth before storing newly harvested potatoes. Furthermore, physical protection is needed to prevent moths entering the stores. This is especially important to prevent infestation of the tubers through young unprotected potato sprouts. If this is not done, managing the moth in potato stores with alternative control measures (instead of systemic insecticides) will have little effect. Use of commercial pheromones to disrupt mating of PTM seems economic in potato stores and helps to monitor the pest during storage.

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