What is happening with climate and potato late blight [*Phytophthora infestans* (Mont.) De Bary] in Bolivia

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Abstract

In the present case study we make reference to the literature available in Bolivia and other countries, regarding the advances in knowledge and control of late blight (*Phytophthora infestans*) in potato. *P. infestans* as a causal agent of the most fear disease that affects potato cultivation, for many years have caused great losses in different parts of the world. The advances in knowledge about the pathogen and the development of integrated disease management are analyzed here through the use of chemical strategies and resistant cultivars with high yield potential. In addition, the effect of climate change is analyzed as well as the implications of late blight and the crop sowing season changes. Finally, we made some considerations of integrated management that may help to face this problem that causes great losses to the poor farmers of the Andean and inter-Andean areas of Bolivia.

Keywords: Losses, cultivars, breeds, virulence, pathogen.

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Introduction

Late blight [*Phytophthora infestans* (Mont.) De Bary], called in Aymara *Llejte* or *Llejti* and in Quechua *T'octu* or *Jauch´a,* is one of the most devastating diseases in potato worldwide. In Bolivia, late blight is the most important disease in wetlands, affecting about 20 thousand hectares of potato production, of which a large part is dedicated to seed production. Late blight compromises the economy of about 40 thousand farmers families (Gandarillas and Ortuño, 2009). In these areas, late blight can devastate potato crops in two to three days and losses can reach up to 100% due to ignorance of adequate chemical control strategies by farmers (Navia et al., 2009).

For late blight control, there are a wide range of systemic and contact fungicides, which are applied between two to 10 times with backpack pumps at 30% below the recommended dose. Generally, a good coverage of the sprinkled plants is not performed and the intervals between applications are long. Farmers generally make 16 applications in very late blight areas. In some cases, mixtures of two or more systemic fungicides (so-called combos) or only systemic are used in a large number of applications. As a consequence, late blight attack is severe and the plots are commonly abandoned (Navia et al., 2009).

Late blight attacks potato at any stage of crop development, affecting the leaves, stems, fruits and tubers. The first symptoms frequently begin in leaf buds, presenting themselves as small light green to dark spots that turn into moisten brown lesions in favorable conditions, their progress is very fast affecting the entire foliage. Sometimes a light green to yellow halo appears around the lesion (Coca-Morante, 2012).

In high humidity conditions, a whitish sporulation (villus) becomes visible, especially on the underside of the leaf. These are the structures of the pathogen: sporangiophors and sporangia. The sporangia are spread by wind and rainwater causing the disease to spread rapidly from the first infected leaflets, to all the leaves and thus to all the plants of a plot, causing their death in a few days (Coca-Morante, 2012).

The stems and petioles have elongated dark brown necrotic spots, with a vitreous consistency that can be easily broken by the action of the wind, hence the Quechua name of *p'aki-p'aki* (brittle). Tubers are infected by sporangia washed by the rain from leaves and stems, which penetrate the ground until tubers are reached. This infection is called *k'anura* by farmers in Quechua. Affected tuber's surface has a slightly sunken irregular area with moisten dark brown spots, and a light brown to dark cork rot is observed in the inside of the tuber. Infected tubers are the main source of inoculum for the next agricultural campaign (Navia et al., 2009).

Distribution of late blight in Bolivia

Late blight has a great capacity for dissemination, wintering in the form of mycelium in infected potato tubers, this mycelium spreads in the tissues of these tubers and reaches the new shoots starting the dissemination to other plants. The dissemination can be initiated from plants or *k'ipas* developed from diseased tubers, or potatoes that were deposited in piles of waste.

Late blight is widely distributed in potato producing areas (Figure 1), from the north to the south of the eastern side of the Eastern Andes (Fernández Northcote et al., 1999; Navia et al., 1999; Coca- Morante, 2012; Coca-Morante and Tolin-Tordoya, 2013). According to these studies, late blight is present between 2800 to 3500 masl, although the presence of the pathogen may be in lower and higher areas at these ranges. In Bolivia, late blight incidence areas are located in the communities of: Morochata, El Choro, Falsuri, Cocapata, Independence, Colomi, Candelaria, Corani, Chullchungani, Monte Punku, Lope Mendoza, Epizana, Escalante, Tiraque, Arani, Capinota, Valle Alto, Valle Bajo and Mizque in the department of

Cochabamba; Comarapa, Los Pinos, Verdecillos, San Isidro, Saipina, Rio Nuevo, Los Negros, San Pedro, San Marcos and Valle Grande in the department of Santa Cruz; San Andrés, La Huerta Concepción, Iscayachi, Pilaya, Entre Ríos in the department of Tarija; Tacacoma Sorata, Inquisivi, Mohoza, Irupana, Coroico, Charazani, Chullna, Puerto Acosta, Amarette, and Moyapampa in the department of La Paz; The Cordillera de El Rosal, Culpina, Incahuasi in the department of Chuquisaca; and in the lower parts of the Departments of Potosí and Oruro (Fernández Northcote et al., 1999; Gandarillas and Ortuño, 2009; Coca-Morante, 2012; Coca-Morante and Tolin -Tordoya, 2013; Gabriel et al., 2013). The locations mentioned above were mapped in a GIS system based on their latitude and geographical longitude presented in Figure 1.

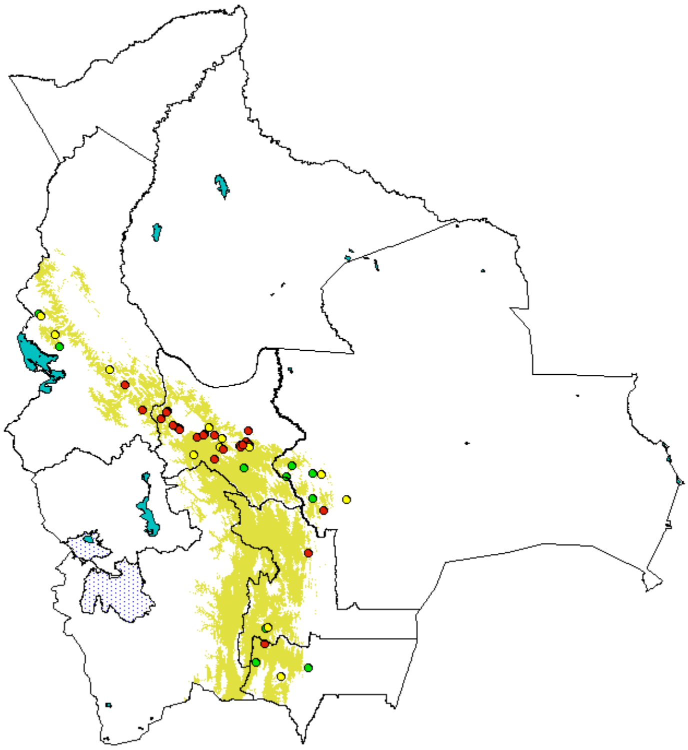

Figure 1. Distribution of *P. infestans* in Bolivia. Own elaboration

Sample collection (n = 51) analyzed in the field and in the laboratory identified the zones with high incidence (red circles), low incidence (green circles) and intermediate incidence of late blight (yellow circles) (Figure 1). These sites are distributed throughout the potato producing area in Bolivia from 1188 to 3966 meters above sea level according to the map altimetry (light brown area) (Prepared by Dr. Bruno Condori).

According to the studies found about the presence of late blight in Bolivia, the disease is distributed throughout the potato production areas, where according to their pathogenicity they are classified into two main ones: the high incidence late blight areas, which have a very favorable climate for pathogen development with warmer temperatures, in addition to intense rainfall, therefore in this area the attack of the pathogen usually occurs from early stages of the agricultural cycle when the plants are still small. In the low incidence late blight areas, the appearance of late blight is not frequent in the early stages of the agricultural cycle, due to colder average temperature conditions and less intense precipitation than in the other zone, thus reducing the chances of late blight attack (Navia et al., 2009).

Biology and epidemiology of late blight in relation to climate

The genus *Phytophthora* belongs to the class Oomycetes, phylium Oomycota, Chromist kingdom. This phytopathogen whose name in Greek means destroyer of plants was initially classified as a fungus due to its filamentous forms similar to hyphae, until the analysis of the rDNA sequences and the composition of its cell wall related it more closely with brown algae and diatoms that with fungi (Pérez and Forbes, 2008; Nieva, 2012). In addition, unlike true fungi, Oomycetes present meiosis in gametangios, being their vegetative nuclei of diploid nature.

The members of the genus *Phytophthora* are heteroconte organisms characterized by zoospores propelled by flagella of variable length and morphology, a mycelium of cenocytic hyphae (without septa), and the cell wall composed of cellulose. *P. infestans*, has two sexual compatibility groups (GC): A1 and A2 (Nieva, 2012). In Bolivia, the studies carried out showed that *P. infestans* populations are of the type of sexual mating A2 and, the absence of mating A1 was assumed (Silver, 1988), so it was considered as an asexual population.

Based on the polymerase chain reaction (PCR), Judelson et al. (1996), developed specific primers capable of amplifying a 1400 bp fragment of the S1 locus present only in type A1 isolates, and absent in type A2 isolates. The same authors also designed molecular markers CAPs (Cleaved Amplified Polymorphic Sequence) capable of amplifying the same DNA fragment in isolates of type A1 and A2, but that after digestion with a restriction endonucluease allows to differentiate both groups by presenting variation in length of the fragments generated. These markers were used by researchers from Bolivia, reporting that late blight populations are rather belonging to the type A1 mating group (Gabriel et al., 2018), this is a new paradigm and calls into question the non-existence of the A1 type. The use of the molecular markers mentioned in the opinion of several experts is still unreliable, so it would be convenient to make new studies on late blight populations in Bolivia, which confirm the presence and/or absence of the A1 type.

It was confirmed that the late blight races found in the areas of Morochata, Colomi and Anzaldo in Cochabamba, Tarabuco and Lampacillos in Chuquisaca, Betanzos in Potosí and Colquencha in La Paz, are complex (Plata, 1998; Colque et al., 2011; Gabriel et al., 2018) and of high genetic variability with an average of seven virulence genes. The most frequent virulence genes found were 1, 3, 7, 10 and 11, less frequent on 2, 4, and 6, and infrequent on 5, 8, and 9. No new populations of late blight product of sexual recombination were found. However, studies conducted by Gomez-Alpizar et al. (2007) in mitochondria and nuclear genes of *P. infestans* from different isolates from Mexico, Peru, Ecuador, Bolivia, Brazil, Costa Rica, Mexico, United States and Ireland, reported that the center of origin of this pathogen could be in South America, particularly in Bolivia and Ecuador.

Regarding the cycle of the disease, late blight develops and sporulates in conditions of high humidity (fog or precipitation), thus producing the primary inoculum. Once the primary infection has been carried out, dissemination occurs rapidly through sporangia that in turn release zoospores that are transported by water and wind, infecting leaves of healthy plants. After a period of incubation of only three to four days in infected plants, new zoospores are formed that constitute the secondary inoculum that will spread the disease in the same plot and the adjacent ones, constituting the secondary cycle of the disease that is repeated several times during the cultivation period (Cooke et al., 2011). The infection of the tubers occurs when the rain transports the sporangia from the leaves and stems to the ground. The tubers may rot as a result of a secondary infection caused by other pathogens.

The biological cycle of the pathogen and the intensity of infection of late blight in potato varies according to environmental conditions, defining areas highly conducive to its development as others that are not as optimal for the development of the disease (Cooke et al., 2011). Based on this criterion, two contrasting sites of Figure 1 were identified, a high incidence late blight zone located north of the crop map (Irupana) and another with low incidence late blight zone located south of the map (Iscayachi), for these sites an analysis was performed climate based on historical monthly temperatures and rainfall.

The high incidence late blight zone in Irupana is defined by an average rainfall of 816 mm with an average temperature of 15.6°C, however the low incidence late blight zone in Iscayachi, is defined by 646 mm of precipitation and an average temperature of 16.5°C (Figures 2A and 2B). Similar results are presented when the averages of all sites are grouped for temperature and precipitation (data not shown), thus, high incidence late blight areas are defined by accumulated rainfall between 650-1700 mm and average temperatures of 18°C; while low incidence late blight areas, rainfall is less than 650 mm with minimum temperatures greater than 11°C.

Figure 2 shows that the humidity conditions due to rainfall, define the ability of the pathogen to be accommodate (Figure 2A), however, neither the average temperatures (data not shown) nor the maximum temperatures (Figure 2C) define clearly the suitable habitat for late blight. In contrast, according to Figure 2B, the higher the minimum temperature (greater than 10°C), this seems to be the limit thermal threshold for the development of late blight in Bolivia. Henfling (1987) indicates that the most favorable temperature for the development of the fungus (mycelium, sporangia) is 21°C. However, temperatures between 0 to 28°C can allow the survival of the fungus in host tissues.

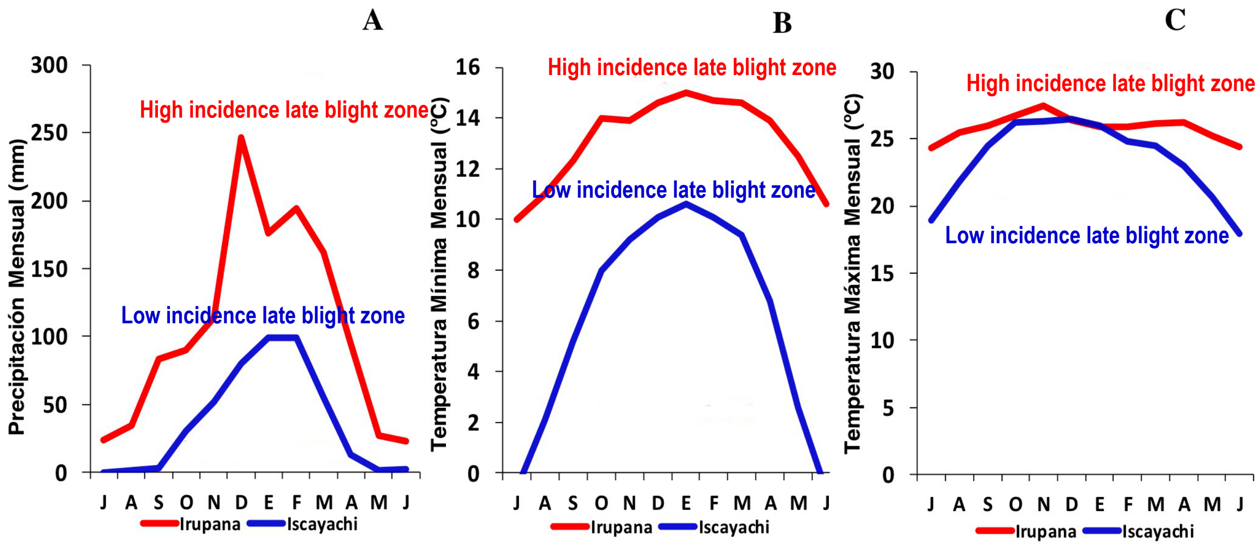

Figure 2. Average monthly precipitation (A), minimum monthly temperature (B) and maximum monthly temperature (C) in a high incidence late blight zone in the town of Irupana and a low incidence late blight area in the town of Iscayachi (prepared by Dr. Bruno Condorí).

Figure 2 shows the high incidence late blight areas (Irupana case), where the minimum monthly temperatures are not so extreme (greater than 10°C) and high amount of rainfall (800 mm accumulated), the late blight attack develops and spreads more rapidly favoring the disease cycle. In low incidence late blight areas (Iscayachi case), the monthly minimum temperatures are extreme (less than 10°C) and low amount of rainfall (less than 650 mm accumulated) which generate unfavorable conditions for the disease and may temporarily prolong or interrupt the cycle. Likewise, the maximum monthly temperature differences apparently do not clearly define the differences between the two zones. These climatic patterns are close to the affirmations of Fernández-Northcote et al., (1999), who infer that minimum non-extreme temperatures (greater than 10°C), require high humidity for the production of zoosporangia, release of zoospores and penetration into plant tissue.

Based on the climate and the biological nature of late blight, several models of prediction of the development of the disease have been generated, validated and put into practice in the United States of America and Europe, as support tools in decision-making for the application of fungicides. In Latin America, disease modeling has been validated by Juarez et al. (2001) and Andrade Piedra et al., (2005) and reported in Condori et al., (2016). The models developed allow the rational use of fungicides, regulating the frequency of application and avoiding unnecessary sprays, these are based on records of relative humidity, temperature and precipitation, which are analyzed in a computer to announce the action to be taken. Among the models that predict the occurrence of late blight we can mention the CASTOR System, BLITECAST, SIMCAST, NEGFRY and LATEBLIGHT (Juarez et al., 2001 and Andrade Piedra et al., 2005).

Impact of late blight on the economy and food security

Potato is a crop of importance in food security for the population of Bolivia. It constitutes the main source of food and income for more than 130 thousand small farmers families which comprise between 30 and 40% of the total peasants of the country. Most part of farmers are of low economic resources and the area they use is not more than one hectare. Per capita consumption of potato is between 43 to 83 kg/year (Zeballos et al., 2009). About 130,000 hectares are dedicated to potato cultivation, with an average yield in the Bolivian Andes of 5 t/ha, while the world is 14 t/ha and 26 t/ha in developed countries (Zeballos et al., 2009).

In economic terms, late blight is one of the most important diseases of potato cultivation. It is estimated that in Bolivia more than 40 thousand families of potato farmers are affected by late blight. In the 20 thousand hectares of potatoes affected, the disease causes a direct loss of around US $ 30 million/year (Fernández-Northcore et al., 2009). Most of the affected area is in seed producing regions that currently only cover 5% of the national minimum quality seed needs. This indirect loss caused by the disease magnifies the importance of late blight in Bolivia as a limiting factor in the production and productivity of potato cultivation, the most important crop in the country's agricultural economy.

As a result of late blight and lack of knowledge for a chemical control strategy, the farmer developed a culture of evasion of the disease either in time, through the use of other planting seasons in which the disease does not occur or occurs with more irregularity, or in space, cultivating at times of greater incidence of the blight, sowing in the parts of higher altitude (more than 3400 masl) where lower temperatures (minimum temperatures below 10 ° C) are not favorable for the development of the disease. The culture of escape the disease implies a low productivity of the area under cultivation that does not match the contemporary concern of increasing productivity for environmental reasons and the present and future food needs (Fernández-Northcote et al., 2009).

Based on the information of the distribution of *P. infestans* in Bolivia presented in Figure 1, the most favorable climatic environments for the presence of late blight in different ecological niches in a current (historical) scenario and a scenario with future projection to the 2050. The spatial modelling of the presence of species by ecological niche is described in detail in Patiño et al., (2008). As a result of the previous analysis (Figure 3), when we compare the surfaces for the presence of late blight in a current scenario (Figure 3A) and a future scenario to 2050 (Figure 3B), it is noticed that the potential surface to accommodate late blight in the future it will increase by at least 17% compared to the current area, that is, the presence of late blight in productive plots with climate change by 2050 could reach 30 thousand hectares more with characteristics of being infected with late blight. On the other hand, it is warned that new climatic niches for late blight would be enabled in higher areas (Figure 3C) especially in the northern part of the Eastern Andes mountain range north of Lake Titicaca (Figure 3).

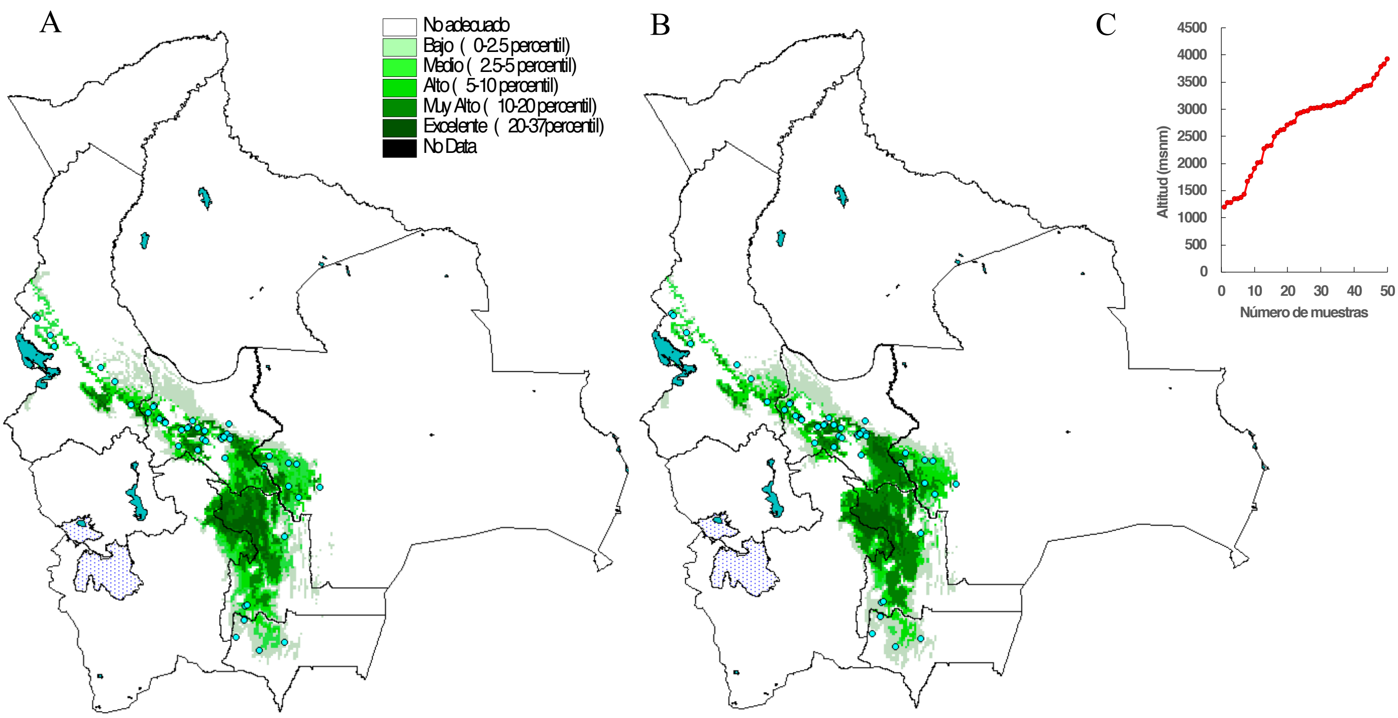

Figure 3. Distribution of *P. infestans* in current scenario (A) and future scenario to 2050 (B) in Bolivia. Altitude in masl of the late blight samples collected (C) described in the studies in Bolivia. Own elaboration

The probable rise in the presence of the pathogen to higher areas (greater than 4000 meters above sea level) would have a crucial impact due to the fact that the seed areas of quality or certified potatoes are found in the high areas, if late blight manages to adapt to these new conditions environmental, it would be a much greater danger due to the losses that it would cause in the production of quality seed, but even more, there would be the possibility that through the seed tuber the disease is distributed, aggravating the problem of dispersion and infestation of late blight towards new zones. At present, symptoms of late blight have already been seen in the community of Cariquina Grande at more than 4000 meters above sea level, not seen to date based on the testimonies given by farmers, apparently there are years that appear and others do not, it is believed that for its appearance certain climatic conditions are combined that facilitate or damage the biological cycle of the blight.

Practices with adaptation related to the integrated management of late blight

Since 1992 PROINPA researched and developed strategies for the control of late blight both in susceptible cultivars and to complement the genetic resistance of the cultivars available in the country. PROINPA's strategy proved to be effective and efficient for the control of late blight, using less fungicides, achieving higher yields (45% more) and greater economic benefits for the farmer.

At present, these strategies are in a transfer and dissemination phase as components of an integrated late blight management combined with traditional knowledge (Fernández-Northocte et al., 2009), as the farmers do not have weather stations, but recognize and associate the presence of rainy nights, sunny days and fog with the presence of late blight, and based on this experience they make decisions to perform fungicide applications.

In order to avoid or reduce the losses caused by this disease, PROINPA developed an integrated late blight management strategy, which reduces costs, protects the health of the farmer and represents less damage to the environment. Integrated late blight management includes several components such as the following:

Cultural practices, during the sowing season, the selection of the plot, elimination of voluntary plants or *k'ipas*, selection of cultivars according to their resistance, use of healthy seed, adequate distancing between plants and furrows, high hilling should be done, reduced transit through the field, cut foliage, avoid harvesting under wet conditions and store only healthy tubers.

Induced systematic resistance, a technology that PROINPA is developing based on the concept of Induced Systemic Resistance, which refers to the increase in the resistance of a plant to pathogens when treated with microorganisms (natural soil), causing systemic protection of the whole plant, against a range of diseases caused by fungi and bacteria. Among these microorganisms, bacteria of the genus *Bacillus* (*B. subtilis* and *B. amyloliquefasciens*) are found (Navia et al., 2019).

Resistant cultivars, PROINPA's potato breeding program obtained new cultivars with horizontal resistance (residual resistance) to late blight, including: Robusta, Jasper India, Puka Huaycha, Aurora, Puyjuni Imilla, Palta Chola, Jatun Puka, among others. (Gabriel, 2010; Gabriel et al., 2011). The use of improved cultivars with horizontal or polygenic resistance is the most suitable control alternative for farmers, the incidence and severity of the disease is lower, the number of applications of fungicides and/or biofungicides is reduced to one or two per crop cycle, the cost of control is reduced, the health of the farmer and the environment are preserved.

Regulatory provisions, a better integrated management of late blight will be carried out when farmers in a given area commit to a coordinated action to execute each of the components of integrated management. Integrated late blight management is less effective if a farmer practices it and his neighbour does not. The durability of the resistance of a variety will be of a greater number of years if its use in space and time is coordinated (Gandarillas and Ortuño, 2009).

Ecological management is based on the efficient use of biofungicides such as Fungitop or the least possible amount of chemical fungicides (http://www.biotopbolivia.org/bt/index.php/es/nos).

It is designed for the most widespread susceptible cultivars in the country such as Huaycha, Sani Imilla and Desirée, and for resistant cultivars such as Runa, Toralapa, Musuj, Robusta, Jaspe, India, Puka Huaycha, Aurora, Puyjuni Imilla, Palta Chola, Jatun Puka, etc. (Gabriel et al., 2011)

In resistant crops, the onset and development of the disease is much slower than in susceptible cultivars. This fact allows to integrate the use of resistant cultivars with a control with biofungicide and/or fungicides that begins when the first symptoms of the disease are observed. Biofungicides can replace contact fungicides (Navia et al., 2019).

Ecological management strategy

Preventive application of biofungicides or fungicides at 10 days after 80% emergency, that is before late blight appears. The frequency of application should be 7 to 14 days depending on weather conditions, very favorable or unfavorable, respectively. Alternation of a systemic and contact product and the non-use of systemic fungicide more than three times (Fernández-Northcote et al., 2009).

It is very important that the first application of the fungicide is carried out in a preventive manner, before the first symptoms of the disease appear (Fernández-Northcote et al., 2009).

It is recommended that applications begin with a systemic fungicide in a very blunt climate zone (Fernández-Northcote et al., 2009). In a not very blinding climate zone, applications can start with an eco-fungicide or contact fungicide.

Adaptable practices related to integrated late blight management

When rain delays, farmers are also delaying planting, which causes susceptible cultivars in their early stages of development to be favorable for pathogen attack. To prevent drastic losses, it is recommended to follow the strategy for susceptible cultivars.

Considering in areas near Lake Titicaca, where farmers are unaware of the disease, there could be genetic erosion of native cultivars due to ignorance of the disease management and could also easily cause resistance to fungicides.

An alternative to this problem is the use of resistant cultivars, in these essays some cultural practices such as low planting densities, timely harvesting, weeding and elimination of voluntary plants or *k'ipas* should also be considered. In turn recommend the use of the strategy of resistant cultivars.

The development of early cultivars with some tolerance to drought, would allow to maintain the dates of the sowings.

Constant monitoring of the traditionally late blight zones, low incidence of late blight areas and areas of possible risk, it will allow to adjust or develop new tools for the management of the disease.

The indiscriminate use of pesticides, resistance, increase in the number of applications, displacement of the crop to higher areas or replacement of the crop by others must be updated in the different areas that are occurring with native cultivars.

Conflicts of interest

The authors declare that this document has no conflicts of interest.

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