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Implications for a warmer, wetter world on the late blight pathogen: How CIP efforts can reduce risk for low-input potato farmers

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This paper discusses the relationship between climate change and the risk associated with a notorious and devastating plant disease. Before exploring the topic in more detail, it is worth noting that the 150-year history of this disease has been characterized by changes in risk to small-scale potato farmers, although the factors affecting those changes were different from climate change. For different reasons, farmers have had to adopt new strategies to cope with increased disease severity. At times, adaptation has been successful, at times not - with dire consequences. Some adaptation strategies have led to undesirable externalities that eventually bring into question the sustainability of the system. All these issues are potential lessons for efforts to intervene in scenarios that are expected to unfold in a wetter and warmer world.

Late blight of potato exploded into the public consciousness in the mid 1840s when the oomycete pathogen, *Phytophthora infestans,* was introduced into northern Europe. The new disease caused by this pathogen affected both foliage and tubers (Figure 1), devastating potato production with highly variable consequences in different regions. The most drastic consequences occurred in Ireland where late blight of potato was the proximate cause of the Irish Famine of the 1840s, which led to a rapid decimation of the Irish population due to both emigration, and starvation and hunger related diseases (Nelson, 1995). The case of Ireland is a clear example of farmers not employing successful adaptation strategies. The reasons for this are complex and involve socio-economic forces that go beyond the simple lack of technological solutions (Bourke, 1993).

It is not clear how other northern European farmers adapted to late blight in the decades that followed the introduction of the pathogen, but potatoes continued to be produced during that period. Robinson (1996) hypothesized that there must have been relatively high levels of resistance in the potatoes grown, a situation that resulted from high selection pressure (susceptible potatoes died) and lack of other strategies. Apparently potato breeding and selection for resistance was an important activity in Ireland during the decades following the famine (Dowley, 1995) and a number of cultivars with resistance to late blight were available in Europe by the late 1800s (Umaerus et al., 1983).

Fungicides – an effective strategy with negative externalities

About 40 years after late blight hit Europe, a French professor, Pierre Millardet, discovered that a mixture of copper sulfate and lime (later named Bordeaux Mix), used to deter people from stealing grapes, also protected plants from fungal and oomycete pathogens. This ushered in the new era of chemical protection of plant disease, but in the view of some it came at a high cost. According to Robinson (1996), the discovery of Bordeaux Mix had a profound negative effect on potato breeding for resistance to late blight. Robinson's premise is supported by the fact that during the Bordeaux Mix era, from the 1880s until the First World War, several highly susceptible varieties (e.g., Bintje, Russet Burbank) became popular. It is difficult to imagine how this could have happened without chemical protection.

Over the years, the role of fungicides in potato production has increased, and presently, spraying is a normal part of production world wide. After Bordeaux Mix, other copper compounds were shown to be more effective; one of these, copper oxychloride, is still used to control blight. Dependence on copper based compounds for potato production was such that a major famine occurred in Germany during World War II when all copper supplies were commandeered for the war effort (Carefoot & Sprout, 1967).

In the 1940's the ethylenebisdithiocarbamates (EBDCs), which are "organic[1]" fungicides, were first introduced into the market. Several of these, zineb, maneb, metiran, mancozeb and propineb make up the group of fungicides most frequently used against late blight in many parts of the world. Mancozeb is the most commonly used fungicide in Ecuador (Crissman et al., 1998) and many other developing countries.

There was hope that late blight risk could be greatly reduced when in the 1970s new systemic fungicides were developed (Schwinn & Margot, 1991). The most effective of these are the phenylamides, such as metalaxyl, ofurace, oxadyxil, and benalaxyl. These fungicides are highly systemic and have a strong curative effect, i.e., they can contain or kill the pathogen even after it is in the plant. The main disadvantage of the phenylamides is that resistance to this chemical compound readily develops in the

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[1] Based on chemical compounds having a carbon basis

pathogen population. Thus, they have come and gone in many parts of the world. Guidelines were developed for the use of phenylamide fungicides (Anonymous, 1992) and in some cases these have worked, leading to continued successful use of the products. In the last decade a number of systemic and translaminar fungicides were developed, and although none has the efficacy of the phenylamides there is less risk of resistance developing in the pathogen population (Bradshaw, 2006).

The strategy of managing late blight by applying fungicides has been the most widely adopted but it has at least two major drawbacks. The first is cost. One recent study estimated that about $77 million are spent on fungicides per season in the US (Guenther et al., 2001). Yearly fungicide usage for late blight control in Europe is estimated to be about $150 million (H. Schepers, personal communication). CIP has made a global estimate for fungicide use in developing countries at $750 million. Based on these estimates, about $1 billion per year is spent on fungicides to control late blight in the US, Europe and developing countries.

The second drawback with the fungicide strategy is the risk to human health and environment. Most of CIP's internally generated knowledge about pesticide effects come from the Andes and, unfortunately for the purpose of this paper, it is difficult to separate the fungicide effects from the overall effect of *highly hazardous and mutagenic* (HHM) pesticides. Nonetheless, fungicides for late blight are the most frequently used of all potato pesticides (Crissman et al., 1998; Sherwood et al., 2001) and farmers often mix compounds in the sprayer; fungicides and insecticides are applied together.

The health risks related to pesticides in developing countries and in this case, fungicides for late blight control are elevated for several reasons. First, EBDCs are among the most commonly used compounds in late blight control in many developing countries (Sherwood et al., 2001). EBDCs break down into ethylenethiourea (ETU), which is a Type IIB carcinogen and an antithyroid compound (Panganiban et al., 2004). EBDCs are also known as skin irritants and high levels of dermatitis were attributed to these products in Ecuador (Cole et al., 1997). Both mancozeb, the most commonly used EBDC, and chlorothalonil, a non-EBDC, were considered highly dangerous for low-input farmers by Wesseling et al (2005).

The second reason pesticides are so dangerous in late blight management in developing countries is exposure of farm workers and family. CIP's health related work has demonstrated that most farmers do not use protective clothing, when mixing or applying (Figure 2) pesticides (Sherwood et al., 2005; Arica et al., 2006). Farmers also do not have special clothing for applying pesticides, nor do they frequently wash clothing that has been exposed (Arica et al., 2006). Exposure goes beyond the farmer, as family members also come in contact with dangerous compounds (Yanggen et al., 2004).

A third factor affecting the health risk presented by chemical use in late blight control is the frequency of applications required for disease management. Under conditions favorable for disease development, farmers in the Northern Andes may spray between 15 and 20 times per season (Oyarzún et al., 2005). However, unpublished data collected by CIP workers from Indonesia cited much higher numbers, with farmers spraying virtually every other day (F. Ezeta, personal communication).

Pathogen dynamics – the continuous source of change

The introduction of *P. infestans* into Ireland is not the only documented case where pathogen movement has resulted in a new challenge to potato producers. Papua New Guinea (PNG) was one of the few countries in the world where potato crops had remained free of potato late blight. That changed in February 2003 when reports of a disease devastating potato crops were received from the Sirunki area in westernmost part of the country. Examination of leaf samples by scientists from NARI (National Agricultural Research Institute) and NAQIA (National Agricultural Quarantine and Inspection Authority) confirmed the identity of the pathogen as *P. infestans* (reported 5 March 2003 in ProMED-mail {http://www.isid.org}, International Society for Infectious Diseases). The spread of potato late blight within s few months from west to east across the highlands of PNG had disastrous consequences for the potato producers in these areas. The combination of an aggressive pathogen, very susceptible host (cv. *Sequoia*), suitable environmental conditions and the absence of chemical control strategies led to almost complete devastation of the potato crop in 2003 (Pitt & Wicks, 2003).

Other examples of pathogen dynamics affecting potato producers do not involve introduction of the pathogen to a new area, but simply change in the pathogen population. Until recently, most isolates of *P. infestans* found outside North America belonged to the US-1 clonal lineage, which has the A1 mating type. With only one mating type, the organism could only reproduce asexually. Early population studies led to a hypothesis that US-1 had caused the original epidemics in Europe in the 1800s (Goodwin et al., 1994) and then spread globally, presumably with seed trade (Fry et al., 1993). Originally researchers proposed that US-1 had spread from Mexico to the US and then from the US to Europe (Goodwin et al., 1994). Alternatively, some researchers proposed that US-1 was introduced into Europe directly from South America (Tooley et al., 1989; Andrivon, 1996). Recent analyses, however, of mitochondrial DNA of *P. infestans* in herbarium material presented evidence that a genotype different from US-1 was involved in the original epidemics in Europe (Ristaino et al., 2001).

During the 1980s, the A2 mating type of *P. infestans* was detected in Europe (Hohl & Iselin, 1984) along with several new alleles for known markers (Drenth et al., 1993). A “new” migration from Mexico had taken place (Fry et al., 1993). The pathogen population in Europe is now highly diverse and there is evidence of sexual reproduction in several European countries (Drenth, 1994; Andersson et al., 1998; Turkensteen et al., 2000; Flier et al., 2003). Furthermore, new populations have been found in Africa, Asia and South America (Forbes & Landeo, 2006). The new migration has become a global reality.

What is the significance of the new populations? Repeated studies have demonstrated that the new populations in Europe and North America are more aggressive than the old population (Day & Shattock, 1997; Kato et al., 1997; Miller et al., 1998; Mizubuti & Fry, 1998; Carlisle et al., 2002). Kato et al (1997); working at Cornell University, used simulation studies to demonstrate that US farmers would, on average, need to shorten spray intervals by 2 days with the new population, and this appeared to fit observations in the field. Scandinavia is another area that has suffered from changes in the pathogen population. In that part of Europe it appears that oospores, the sexual spores that can survive in soil over the winter, are causing disease to occur earlier in the season. Because of the earlier onset of disease, fungicide use has increased four-fold in Finland (Hannukkala et al., 2007). In general, the introduction of new pathogen genotyopes in the US led to a “re-emergence” of the disease, after a long hiatus (Fry & Goodwin, 1997a). Even in the high-tech agricultural context of the US, not all farmers adapted to this change; some lost family farms when crops were destroyed by blight (Fry & Goodwin, 1997b).

The story of changes in the pathogen population is not over for late blight. Parts of sub-Saharan Africa, Chile and some areas in Asia remain as the last refuge of the old population (Forbes & Landeo, 2006) and it is only a matter of time until the new population is introduced into these areas. The rapid disappearance of the old population when the new one is introduced is also taken as evidence of the greater fitness of the latter. The area of sub-Saharan Africa that has the old population harbors some of the poorest potato growers on the planet: Rwanda, Burundi, East DRC and SW Uganda. All research to date would indicate that farmers in that area will need to adapt to more severe late blight when a new population is introduced.

Host resistance – the orphan adaptation strategy

For a polycyclic disease such as late blight, the rate of disease progress determines the increase in severity and reducing this rate is the main goal for disease management. Of all the tactics that one might consider, host resistance is theoretically one of the most effective (Figure 3). Comparative analyses in Mexico of late blight intensity on a susceptible cultivar, Alpha, and a resistant cultivar, Norteña, illustrated how effective a resistant cultivar can be. At 40 days after emergence, disease severity was 100% and 4% in Alpha and Norteña, respectively (Grünwald et al., 2000).

Two phenotypic expressions of resistance have been described in the literature. They have received numerous names (for discussion see Forbes & Landeo, 2006), but the most widely used are probably “horizontal”, for resistance that is good against all pathogen races, and “vertical”, for resistance that is only good against some races. In this paper we will refer to them as “quantitative resistance” (horizontal) and “qualitative resistance” (vertical) in reference to the modes of inheritance in potato progeny. While the distinctive field expressions of quantitative and qualitative resistance constitute a useful working model, some research has tended to blur this distinction. Histological analyses sometimes indicate that the same process of rapid cell death, referred to as a hypertensive reaction, occurs in both resistance types (Vleeshouwers et al., 2000). Researchers have also found that qualitative resistance R genes that have been overcome, i.e., for which the pathogen population is now virulent, may still contribute to resistance and perhaps are components of quantitative resistance (Stewart & Bradshaw, 2001).

In spite of this apparent uncertainty about the nature of phenotypic resistance types, there is an important practical difference that has generally held true. Qualitative resistance was originally considered a silver bullet for late blight control because of its extreme efficacy against avirulent races of the pathogen.

However, virulent races rise to predominance so quickly in the pathogen population that qualitative resistance has been characterized as a phenomenon only found in breeders' fields; there is little evidence it has ever helped farmers (Forbes & Landeo, 2006). In contrast, quantitative resistance has generally been durable. The quantitative resistance of the Mexican cultivar Norteña, mentioned above, and several other Mexican cultivars was found to be durable over a period of 40 years under Mexican growing conditions exposed to a sexual pathogen population (Grünwald et al., 2002). In another recent study, quantitative resistance was found to be stable across a wide range of environments (Forbes et al., 2005). Several cultivars (e.g., Cruza 148) have also held their resistance for decades in Africa (Forbes & Landeo, 2006).

Because of the failure of qualitative resistance to provide protection in farmers' fields, there was a shift in emphasis on the part of breeders toward quantitative resistance that occurred in the 1990s (Bradshaw et al., 1995; Landeo et al., 1995). At this time it would be very beneficial to have a detailed review of progress made, but unfortunately it would probably not be very encouraging. A number of cultivars with quantitative resistance to late blight have been released in developing countries (Table 1), but not many are grown in large areas. There are many socio-economic factors weighing in against the adoption and widespread use of a new potato cultivar, particularly market forces (Walker et al., 2003), and the lack of functioning seed systems in developing countries that would produce the planting material needed for diffusion.

Breeding for a quantitative trait is difficult and in the particular case of late blight, the resistance is often associated with late maturity and day length sensitivity (van der Vossen et al., 2005). These problems can be added to those mentioned above when one tries to explain the slow progress in getting late blight resistant cultivars into the hands of farmers. Recently, some breeders have advocated a search for novel and hopefully "broad spectrum" R genes that can be introgresssed or engineered more rapidly into existing or new potato cultivars (van der Vossen et al., 2005). These genes would, in theory, either be deployed in multi-lines or by pyramiding in a single genotype. Two R genes from the diploid species *S. bulbocastanum* were cloned and expressed after introduction into a susceptible potato cultivar (Song et al., 2003; van der Vossen et al., 2003). The sources of these genes were resistant against all known races of the pathogen, and this has led to great speculation on their durability. Should these genes prove to be durable, they could provide a novel, and extremely effective disease control mechanism.

Late blight risk in a wetter and warmer world

As discussed above, the risk posed by late blight to potato growers has been a historical roller coaster, with highs and lows occurring from man-made interventions (fungicides, breeding) and natural factors (pathogen population dynamics). Less has been documented about the effect of weather on late blight, but the little that has been published demonstrates clearly that late blight is a model case for climate change studies.

Late blight has long been known as a weather – driven disease and this has certainly been a major factor in the development of weather-based forecasting models that assist farmers in scheduling fungicide applications. The U C Davis IPM program maintains a catalogue of 16 models (http://www.ipm.ucdavis.edu/DISEASE/DATABASE/potatolateblight.html). Many models have been incorporated into much more complex decision support systems (DSS), involving monitoring and other disease management tactics (Schepers, 2004). Andrade-Piedra et al (2005) using a metamodelling approach demonstrated that late blight was very sensitive to changes in temperature and humidity, which could be critical factors in determining the role that late blight might play in a potato system's resilience against climate change (Hijmans et al., 2000b).

Farmers have long understood the close link to weather and late blight severity. For example, to avoid high disease pressure they plant at high altitudes where temperatures are below optimum for the pathogen, or they may plant outside the rainy season when low humidity retards disease development (Devaux & Haverkort, 1987). Escaping disease in time and space leads to lower yields as the potato crop is not planted at a time or in a location appropriate for optimal plant growth. Sub optimal production is also characterized by increased risk of crop loss due to frost or drought (Haverkort, 1986).

The weather-driven nature of potato late blight has led to the development of several tools that enhance our ability to explore the relation between this disease and climate change. Of the numerous disease simulators reviewed by Campbell and Madden (1990), the late blight simulator developed by Bruhn and Fry (1981), hereafter referred to as LATEBLIGHT (Andrade-Piedra et al., 2005) was identified as having provided "valuable new understandings of epidemics.....as well as the development of improved disease management practices". The success of this simulator was assumed to derive from the fact that it was developed to solve specific research questions, rather than as an end in itself. LATEBLIGHT, which has been used to test numerous management strategies was also used to develop a late blight forecasting model known as SIMCAST (Fry et al., 1983) that was subsequently adapted for resistant cultivars (Grünwald et al., 2000).

The forecast models SIMCAST and BLIGHTCAST were integrated in a Geographic Information System (GIS) (Hijmans et al., 2000a). This technology can be used for geographic zonation based on potential late blight severity (Figure 1) and can be useful for disease management questions, resource allocation, impact assessment, and exploring climate change scenarios (Figure 4). The strength of the GIS forecasting approach using SIMCAST lies in the link between simulation model, forecasting rules and GIS zonation. The link to simulation can ultimately provide much greater power for biological interpretation by enabling geographic zonation based on parameters that are specific to a particular cultivar, pathogen population or both.

Particular examples of types of geographical maps include 'risk index maps' in terms of severity of disease and associated 'probabilities' or 'uncertainties' of estimates; these may guide both environmental protection management schemes as well as breeding programs towards development of resistant varieties in certain environments. Such maps would be constructed in relation to the crop and thus may also be used to estimate yield losses and optimize agronomic measures in a more quantitative way. Other applications in the future could include an early warning system based on recent weather data using, for example, remote sensing image analysis techniques and actual weather station data.

Zonation can be done with geo-referenced historical weather data sets, but also with weather data generated from climate change models, as has been done for rice leaf blast caused by *Pyricularia oryzae* using disease simulation models linked to GIS (Luo et al., 1998) and more recently when researchers predicted increased range of oak disease as a result of climate change (Bergot et al., 2004). At this time, CIP is participating in two international initiatives in which climate change models will produce local weather data sets that will permit specific predictions of changes in late blight severity in several regions of the world. To date only generalized analyses have been done for the purpose of academic discussion. For example, GIS applications demonstrate visually the expected increase in fungicide needs in China with arbitrary increases in average temperatures or rainfall (Figure 5).

Given the sensitivity of potato late blight to weather conditions, there is little doubt that a wetter and warmer world will present new challenges to potato farmers in many parts of the world. In the section that follows, we will discuss these specific efforts that CIP and partners shall put forth to help low-input potato farmers develop adaptation strategies to meet these challenges.

CIP efforts in the future to reduce risk associated with increasing late blight severity

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Improve tools for studying late blight risk and climate change.

CIP will improve its ability to estimate changes in late blight severity as a result of climate change and other factors. This will be done is several ways. First, via initiatives like those mentioned above, improved weather data will increasingly become more readily available in target areas. This will allow for more realistic targeting and risk assessment. Identification of areas with the greatest risk will facilitate prioritization and resource allocation.

Second, the accuracy of the current modeling technology will be improved through verification and validation exercises that are underway. New approaches are being evaluated for estimating the variables needed to derive late blight models. Models currently being used for geographic predictions were originally developed for plot-level predictions and would require reparameterization for use on local pathogen population and cultivars in GIS. Finally, CIP will align itself with other institutions interested in the study of plant disease and climate change. A recent review article on plant disease and climate change (Garrett et al., 2006) outlines a conceptual framework for organizing research in this area. At the highest level of global effects, the authors identify the need for international cooperation on data collection and synthesis.

CIP recently engaged in an internal targeting exercise for late blight research and development. In that exercise, a number of sources were used, including GIS-based late blight severity mapping, regional priority evaluations and poverty mapping. As a result, four general areas were identified:

- The Central Andean highlands
- The Lake Kivu region of SSA (possibly plus Ethiopia)
- Southwest China, Nepal and Bhutan (potentially plus N. Korea)
- Potentially Azerbaijan and Armenia

In a wetter and warmer world, CIP will have to continuously update this priority setting exercise. Changing weather scenarios may bring new regions onto the priority map.

Get resistant materials into farmers' fields.

CIP and partners must rapidly meet the challenge of breaking bottlenecks that are currently thwarting efforts to increase adoption of resistant cultivars. Integrated, multi-disciplinary efforts will be required as problems exist on many levels: production (breeding), supply (seed systems) and demand (market).

As noted above, previous efforts to develop potato cultivars with high levels of resistance to late blight have been only partially successful. There have been some dramatic failures where previously resistant cultivars became very susceptible after a virulent pathogen population predominated (Forbes & Jarvis, 1994). There have also been important successes. The cultivars Cruza 148 and Rutuku have maintained high levels of resistance in the Lake Kivu region of sub-Saharan Africa for decades (Potts et al., 1985). CIP will have to employ the best methods available to develop an array of cultivars not only with durable resistance but also with many other characteristics to ensure market acceptance. One strategy for durability of resistance is to use a broad genetic base, something that is not present in current cultivated potato (Villamon et al., 2005). To broaden the base, CIP will make better use of its wild germplasm by directed searches for new resistance sources. For example, a molecular phylogenetic analysis that identified four major clades in potato (Spooner & Castillo, 1997), was used to identify a clade (*Piurana)* that had not previously been utilized as a source. A major quantitative trait locus (QTL) for resistance was identified on chromosome 11 of the species *Solanum paucissectum* from this newly “mined” clade (Villamon et al., 2005).

The accuracy of genotypic mapping of resistance often depends on the accuracy of the phenotypic measurement of the trait. CIP is working now to improve its ability to identify resistant types by getting a better understanding of the epidemiological components that make up a resistant phenotype (Chacón et al., 2007), and better understanding the infection process (Oyarzún et al., 2004). Even long-standing scales used for quantifying resistance in the field often can be greatly enhanced to provide much more reliable data (Hansen et al., 2005), and CIP is currently working in this areas (unpublished data).

In order to overcome bottlenecks that have hampered successful adoption of resistant cultivars in the past, CIP will need to innovate. The traditional “binary” working relationship between CIP and the national potato program of each country is giving way to a much broader chain approach involving the private sector, universities, farmer groups, community groups and NGOs. Involving a large number of stakeholders in the complete production marketing chain increases the probability of selecting cultivars that fulfill the needs all. Some of the innovative relationships CIP will need to develop are not simple; finding common ground with private industry on cultivar development will involve complex agreements on property rights.

An important goal of any seed production and distribution system is to shorten the time required to make seed of new cultivars available to farmers; and this is a crucial aspect of cultivar diffusion. Potato has a very low multiplication rate (ca 10x per season) and producing seed of a new cultivar therefore requires several seasons. Where formal seed systems have been used, the introduction of new cultivars can occur rather rapidly. Interestingly, some of the best examples had occurred previously in sub-Saharan Africa. Prior to the 1980’s only very old European cultivars were grown in this region. In the early 1980s formal but simple seed systems were introduced to both Rwanda and Burundi which helped to multiply newly selected cultivars (van der Zaag, 1982; Kayitare & Potts, 1987). This led to an almost complete turnover of cultivars in Burundi, Rwanda and Eastern DR Congo (Walker & Crissman, 1996). Some of the cultivars introduced at that time, Cruza 148 and Rutuku, are still somewhat common in these countries although they are less popular than the more productive cultivars with higher market value when fungicides are available. Unfortunately, because of civil unrest in the 1990s, the seed systems of Burundi and Rwanda completely disintegrated. Rwanda is presently trying to rebuild its system (Crissman, 2002).

CIP will take a user-needs approach to improving formal and informal seed production to enhance cultivar diffusion. One component of this is addressing the need to enhance farmer knowledge on maintaining seed quality in the informal system. Thus, farmer training via appropriate stakeholders (governmental, non-governmental, etc) should be a significant component of any cultivar diffusion effort.

Improve farmers' capacities to manage blight.

Small-scale potato farmers know much about biological entities they can see, such as crops and animals, less about insects - some stages of which they don't see- and almost nothing about microorganisms (Trutmann et al., 1993; Ortiz et al., 2003). When asked "what causes blight", these farmers commonly provide answers that may hint at correlations, but are otherwise incorrect: lightening, low temperature, rain, sun while it rains, stages of the moon, bad seed; some farmers may even give mystical explanations (Ortiz et al., 2003). The historical association between potato late blight and the emergence of the germ theory (Bourke, 1993) lives on in developing countries as agricultural science has had little impact on the knowledge of rural people.

This lack of knowledge about the basic aspects of plant disease makes it difficult to simply teach farmers how to manage fungicides, use host diversity, or utilize any other disease control strategy. For that reason, workers in developing countries have been using knowledge-intensive, participatory techniques to help farmers increase their understanding of how disease occurs and how it can be managed. A number of competencies have been identified that a developing-country farmer needs to manage late blight: correct identification of the disease, correct identification of weather conditions conducive to the disease and basic understanding of the life cycle of *P. infestans*; adequate selection of potato varieties; adequate use of chemical control; and frequent scouting of the plot (J. Andrade-Piedra and G.A. Forbes, *unpublished data*).

To help farmers develop these competencies, CIP and partners engaged in 2005 in a process of developing competency-based farmer training modules. These learning modules help farmers build their competencies to manage late blight by increasing their understanding of factors that affect disease development and of the mechanisms by which different interventions work. The method for developing the modules was based on knowledge management theory, which provides a functional framework for development of training materials in general (Zapata Sánchez, 2005).

The challenge to CIP in a wetter and warmer world will be ensure that farmers in target countries have competencies needed to manage late blight in a changing environmental context. It is imperative that CIP develop linkages with dynamic partners involved in farmer training, including governmental, non-governmental and community-based organizations. CIP and partners will have to stimulate donor agencies to provide the funds needed to reach large numbers of farmers in the many areas where late blight is a problem.

Develop integrated management strategies.

Resistant cultivars require less fungicide than do susceptible cultivars for adequate late blight suppression, but the optimal amount and timing of fungicides depends on several factors, including the time and amount of initial inoculum, weather, and the efficacy of the product. General principles and dynamic decision aids can help farmers optimally apply control products to reduce the risk of crop loss due to disease, as well as potential risks associated with exposure to toxic materials. CIP is currently working on simple guidelines involving fungicide timing, dosage and host resistance for late blight management (Fry, 1975; Fry, 1978). Strategies will be made available for incorporation in training activities and will be validated and updated via participatory research often as part of FFS.

In addition to cultivar resistance and fungicide optimization, some cultural controls have been used as components of late blight management. Sanitation (elimination of sources of the pathogen) is commonly considered the principal component of integrated late blight management. Sanitation, however, will probably have limited effect in tropical countries where the disease occurs year-round. Nonetheless, a number of cultural practices have been tried and warrant further site-specific adaptive research. For example, mulching was used in Africa to maintain soil moisture thus allowing for shifting of planting date and facilitating avoidance of the disease (Devaux & Haverkort, 1987). Host diversity, either as intercropping or cultivar mixtures, has also been found to have positive effects in some cases (Garrett & Mundt, 2000; Pilet et al., 2006).

To help potato professionals better deal with pesticide toxicity, and the notion that not all pesticides are alike, the concept of Environmental Impact Quotient (EIQ) (Kovach, 1992) will be incorporated into late blight research and training. The EIQ is a weighting system that takes into account the environmental impact of a product but also allows for factoring in dosage and frequency. The EIQ also serves as a useful metric for assessing overall progress in any program aimed at pesticide reduction. The EIQ is currently being used with farmers in a FFS context in Vietnam to help them understand the benefits of integrated pest management (Anonymous, 2006).

Develop or exploit new technologies.

In the last decades, with the exception of resistant cultivars and new fungicides, only a few new technologies were developed that provide useful alternatives to potato farmers facing late blight problems in developing countries. However, new formulations of an established fungicide could provide a safe disease management tactic. Use of phosphites, various salts of phosphorous acid, has been known for decades as a safe and effective control for oomycete pathogens (Smillie et al., 1989), such as the one causing potato late blight, but patent constraints restricted development of commercial products for this disease. Those constraints no longer exist and many products with different formulations are now becoming available. Research at the University of Mar del Plata (UNMdP) in Argentina has demonstrated the potential for managing late blight with phosphites, but the effects are cultivar specific. Site-specific, adaptive research to find the best formulations, dosages and application times is needed, making this an appropriate technology to be developed for multi-partner research platforms.

The advantage of phosphites in developing countries is many-fold. First, there is little evidence of resistance development in the pathogen population. Phosphites have both direct and indirect effects in that they are toxic to the pathogen and stimulate resistance in the plant (Smillie et al., 1989). Even if resistance develops in the pathogen, the indirect effect may still hold. Second, the products are highly systemic, which should help guard against infection even when application technology is not optimum, which is frequently the case in developing countries. Finally, the materials pose little risk to human health and environment; phosphites have received an exemption from the US Environmental Protection Agency from the requirement on tolerance.

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Table 1. Late blight resistant varieties released in developing countries

Region	Country	Year of Release	CIP number	Local name
South and Central America	México	1992	720122	Norteña
		1997	575049	Moserrat
		1980	720054	Tollocan
		1971	720044	Rosita
	Bolivia	1996	385240.2	Chaposa
	Colombia	1956	720071	Monserrate
	Costa Rica	1996	386040.9	Birris
		1996	386056.7	Floresta
	Ecuador	1966	720075	INIAP Santa Catalina
		1990	384638.10	INIAP Santa Rita
		1995	388790.24	INIAP Fripapa
		1995	382119.20	INIAP Rosita
		1995	388749.3	INIAP Margarita
	Guatemala	1991	382170.101	ICTA Xalapan
	Panamá	1992	381381.13	IDIAP 92
		1992	381390.30	IDIAFRIT
		1992	382171.10	PRECODEPA
	Perú	1993	384866.5	Amarilis-INIA
		1993	377744.1	Kori-INIA
		1995	380496.6	Chagllina-INIA
		1998	376180.6	Atahualpa
		2000	384688.2	Chota-Roja UNHEVAL
		1999	377740.2	INIA 301
	Venezuela	1987	380013.12	Andinita
Sub-Saharan Africa	Burundi	1980	800949	Sangema
		1993	381381.9	Rukinzo
		1992	381381.26	Ingabire
		1992	382147.18	Jubile
	Cameroon	1992	381381.13	CIPIRA
		1992	381406.6	Tubira
	Ethiopía	1987	378501.16	Sissay
		1995	378501.3	Awash
		1995	374080.5	Menagesha
		1995	800984	Genet
	Kenya	1998	381381.13	Tigone

		1998	381381.20	Asante
	Rwanda	1992	381381.3	Nderera
		1992	381395.1	Ngunda
		1992	383120.14	Kigega
		1992	383140.6	Mugogo
		1992	386003.2	Mizero
		1992	387233.24	Gikungu
	Uganda	1991	381379.9	Kisoro
		1991	381381.20	Victoria
		1991	374080.5	Kabale
	Zaire	?	378699.2	Kinigi
		1995	380583.8	Baseko
		1995	380606.6	Enfula
		1995	386022.2	Nurula

Figure 1. Symptoms of foliage blight (left side) and tuber blight (right side) on potato caused by the oomycete pathogen *Phytophthora infestans* (Courtesy of W. Perez).

Figure 2. Man spraying fungicides on potatoes in Papua New Guinea. Lack of protective clothing is typical of pesticide application in developing countries.

Figure 3. Potato field comprised of two cultivars, one resistant (left side) and one susceptible (right side) to *Phytophthora infestans*, the cause of late blight.

Figure 4. Map depicting global zonation. Predictions based on SIMCAST, a late blight forecasting model, run within a geographic information system (from Hijmans et al., 2000a).

Figure 5. Map depicting zonation of potato production zones based on predicted number of protectant fungicide sprays needed to control late blight in China. The pattern based on historical weather is given in the upper left; the other maps demonstrate visually the expected increases in fungicide needs in China with arbitrary increases in average temperatures of 3 ^{o}C (lower left) or 25% rainfall (upper right).

Foliage blight

Tuber blight

Figure 1

Figure 2.

Figure 3

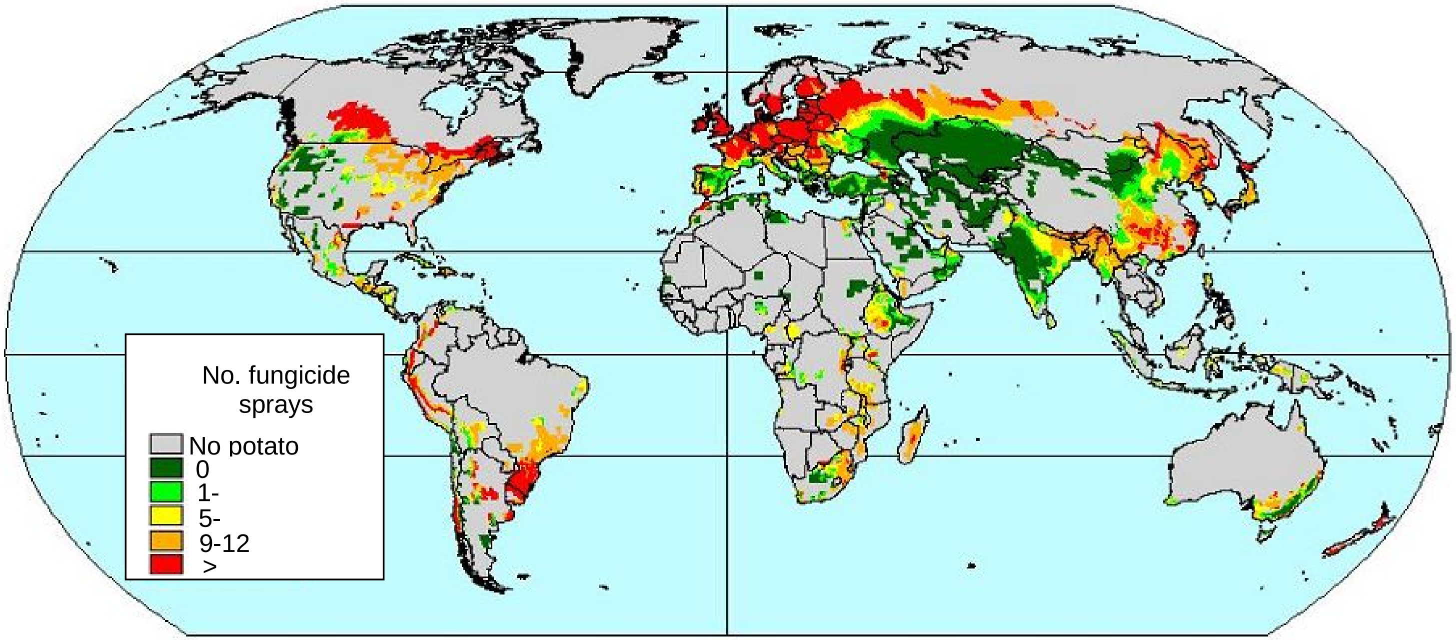

Figure 4

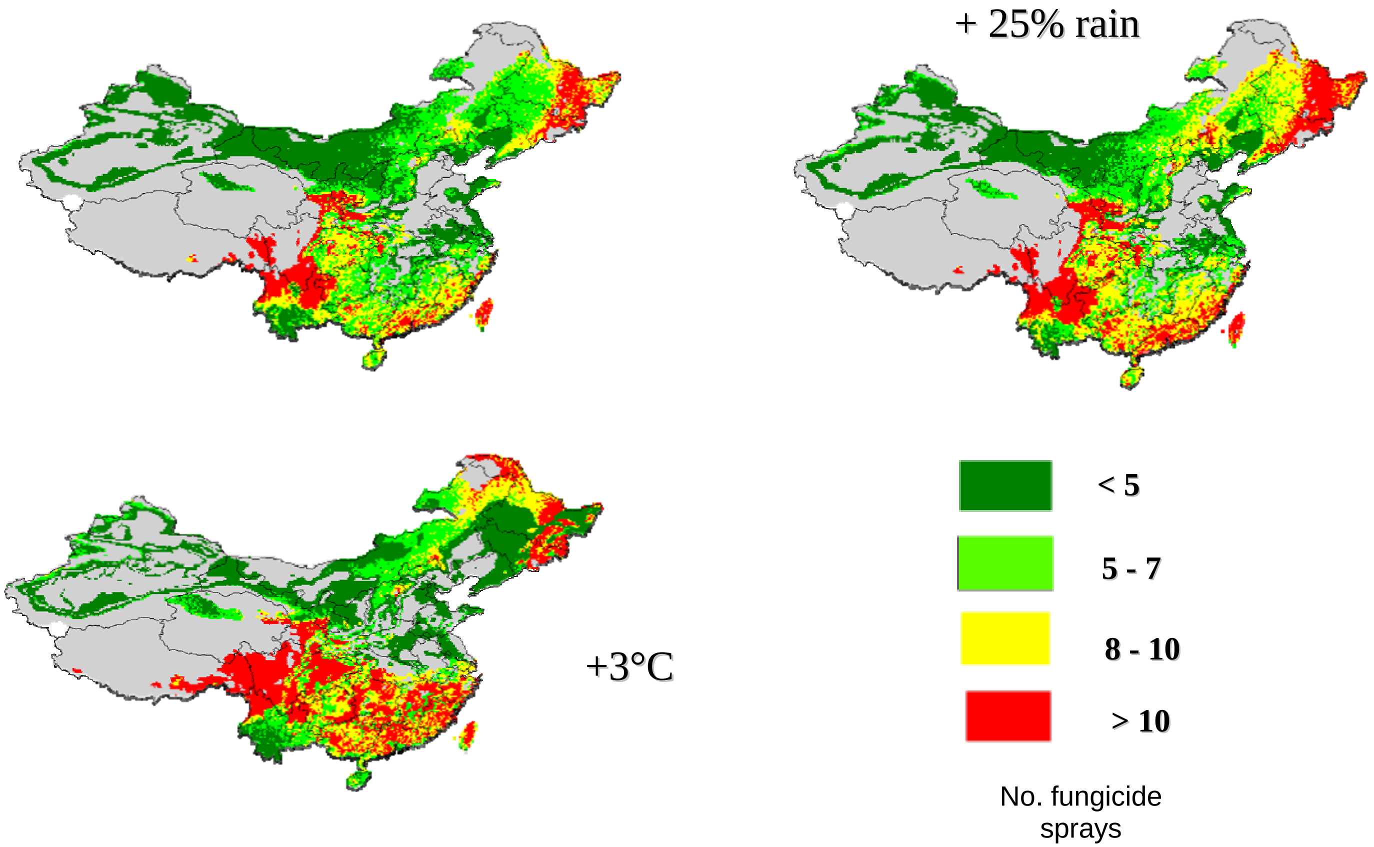

Figure 5