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Computer Simulation Models: A Tool for Transferring IPM Technologies from Developed to Developing Countries

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Executive Summery

The overall aim of this project is to examine the possibility of using computer simulation models as a tool for transferring IPM technologies from developed to developing countries. The feasibility of this approach will be examined by using the potato late blight simulator as a case study. The specific objectives are: i) Simultaneously validate the late blight simulator in temperate and tropical sites; ii) Apply the simulator to several research and management problems; and iii) Document the experience such that the simulators can be useful for disease control and research in other developing countries sharing the same or similar agroecosystem.

In line with the research plan, activities in the second year of the project were focused on objectives # 1 and 2. For objective # 1, the simulator was validated with data of 25 experiments carried out in Ecuador, Israel, Mexico, Peru, and US from 1997 to 2002. A total of 16 potato cultivars and breeding lines with different levels of resistance to late blight were tested under different weather conditions resulting in 50 epidemics. The model accurately predicted the actual epidemics when the number of initial lesions was known but it underestimated the actual epidemics when this parameter was not known. These results suggest that the method of disease initiation is critical for the simulator and we intend to focus on that subject in the next year of the study. For objective # 2, the usefulness of employing the late blight simulator for addressing biological questions was demonstrated using an example from Israel. The model was used to test the hypothesis that the source of the water used for irrigation (fresh or municipal recycled water) affect the rate of late blight development. Based on the simulation experiments, we concluded that the development of late blight in fields irrigated with municipal recycled water is less severe than could be expected based on the suitability of the environmental conditions to the pathogen. In further studies it was found that Boron, a microelement that exists in high concentrations in recycled water, induces systemic acquired resistance against *P. infestans* and also against *Alternaria solani* (the causal agent of early blight).

Section I

A. Research Objectives

The overall aim of this project is to examine the possibility of using computer simulation models as a tool for transferring IPM technologies from developed to developing countries. The feasibility of this approach is examined by using the potato late blight simulator as a case study. The specific objectives are:

1. Simultaneously validate the late blight disease simulator in temperate and tropical sites;
2. Apply the simulator to several outstanding research and management problems;
3. Document the experience such that the simulator can be useful for disease control and research in other developing countries sharing the same or similar agroecosystem.

B. Research Accomplishments

B1. Validation of the late blight simulator

The late blight simulator being validated with data of 25 experiments carried out in Ecuador, Israel, Mexico, Peru, and US from 1997 to 2002. A total of 13 potato cultivars (Alpha, Amarilis, Bolona, Catalina, Cecilia, Gabriela, Katahdin, Kennebec, Mondial, Nicola, Tomasa, Uvilla, and Yungay) and three potato breeding lines (C114, LBR37, and NN) with different levels of resistance to late blight were tested under different weather conditions resulting in 50 epidemics. Data of those experiments was compiled by Marco Taipe and Greg Forbes in the International Potato Center (CIP) at Quito, and includes environmental conditions, disease severity evaluations, fungicide applications, and host development.

The data was first checked and converted into an appropriate format for the simulator. The following parameters were obtained: resistance and maturity level of the cultivar; emergence (date); beginning of the epidemic (date and disease severity [%]); end of the epidemic (date); plant density (plants m^{-2}); plot size (m^2); initial infection (natural or artificial inoculation); and location of the temperature-relative humidity (RH) sensor. The weather variables calculated were average temperature, number of hours when RH => 90%, average temperature when RH => 90% and precipitation, on a daily basis. In some experiments there were more than one temperature-RH sensor, e.g. at 1.5 m and within the canopy. In those cases, weather variables were calculated using data from within the canopy.

The next step was to create a system is SAS (Release 8.02, SAS Institute Inc., Cary, NC) to run many simulations at a time. The SAS version of the simulator developed by Greg

Forbes, Robert Hijmans and Jorge Andrade-Piedra at CIP-Lima was converted into a macro program. The values assigned to the parameters by the user are now considered macro variables that are managed by another program. The system facilitates enormously the process of validation because it allows (i) to test structural modifications of the simulator in many scenarios, and (ii) to make visual comparisons of observed *vs.* simulated variables and statistics. In addition, the simulator is now user-friendlier than previous versions.

With the input data and the software in place the next step was to compare the most important variable output by the simulator, disease severity, with that observed in each experiment. Only uncontrolled epidemics (no fungicides) were considered. Observed and simulated epidemics were compared visually by plotting observed and simulated severity values (y-axis) *vs.* days after emergence (x-axis). In addition, severity values from various experiments were pooled in plots of observed (x-axis) *vs.* simulated values (y-axis) and simple linear regressions between them were calculated. The intercept and the slope of those regressions were tested against the null hypotheses of H_0: $\beta_0 = 0$ and H_1: $\beta_1 = 1$, respectively with a t-test. The experiments were divided in two groups: (i) experiments in which initial infections were the result of artificial inoculation and (ii) experiments in which initial infections were the result of incoming inoculum from outside sources.

In two of the experiments of the first group, individual plants were inoculated using a sporangial suspension. The number of initial lesions resulting from the inoculation was assessed and this value expressed as '# lesions per plant' was used to begin the simulated epidemics. Results from a representative experiment are presented in Figure 1. When all observed and simulated severity values were pooled (Figure 2), the intercept of the simple linear regression was not different than zero ($p = 0.3899$), and the slope was not different than one ($p = 0.3574$). In three other experiments, the whole plots were inoculated and the number of lesions resulting from the inoculation was not assessed. In those cases, the simulator underestimated the observed severity. These results suggest that the method of disease initiation is critical for the simulator.

In experiments from the second group (initial infections from natural inoculum) the parameter '# lesions per plant', which is used to begin the simulated epidemics, was usually not reported. Results from a representative experiment are presented in Figure 3. Comparisons of observed *vs.* simulated severity values for all the epidemics revealed that the intercept was not different than zero but the slopes were always different than one (Figure 4). The meaning is that the prediction ability of the simulator is still non-significant. In addition, preliminary analysis showed that the number of hours when RH => 90% are underestimated when the temperature-RH sensors are located outside the canopy. This is the case in many experiments.

Therefore, the next step in the validation of the simulator will be to develop a method to estimate leaf wetness period within the canopy based on information from outside the canopy.

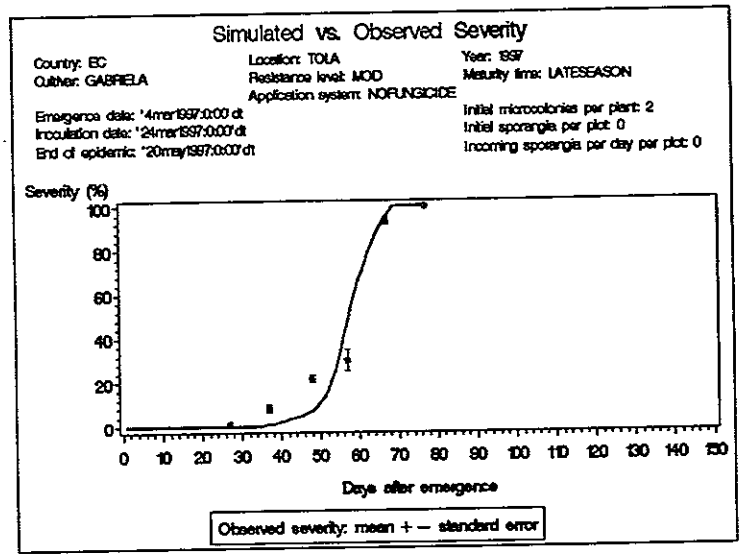

Figure 1. Comparison of simulated vs. observed late blight severity in an experiment that was conducted in La Tola, Ecuador in 1997.

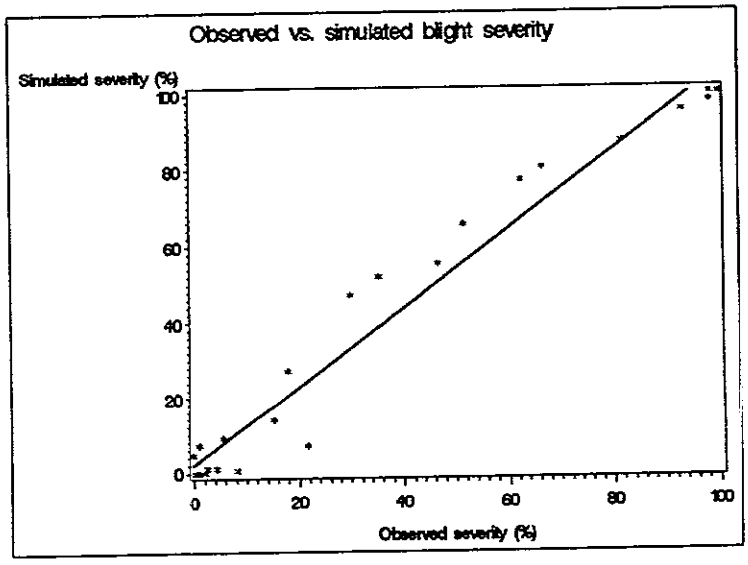

Figure 2. Observed *vs.* simulated blight severity from two experiments under artificial inoculation

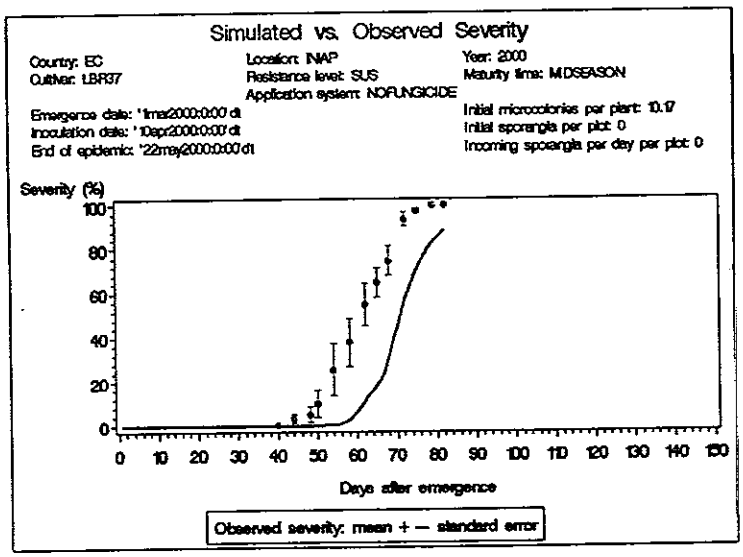

Figure 3. Comparison of simulated vs. observed late blight severity in an experiment that was conducted in INIAP, Ecuador in 2000.

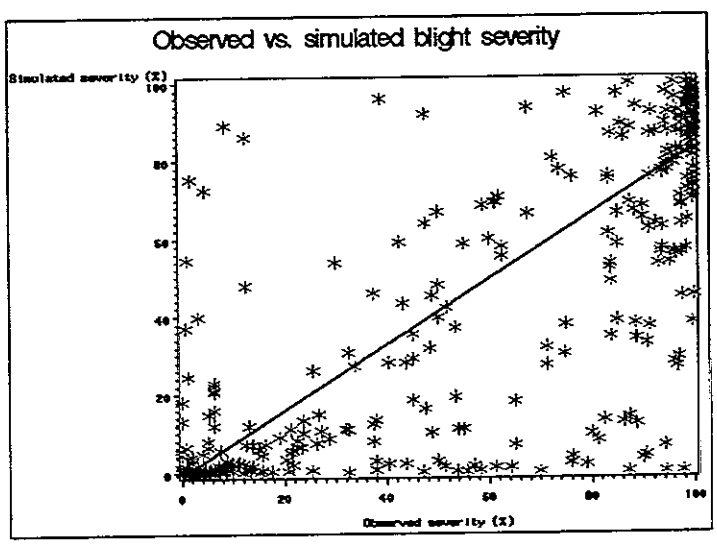

Figure 4. Observed *vs.* simulated blight severity from 21 experiments under natural infection

B2. Applying the simulator to research and management problems

The usefulness of employing the late blight simulator for addressing biological questions will be demonstrated using an example from Israel. First, we will present briefly the background and the research question and then the results of the simulation experiments will be described.

Potatoes are grown in Israel in several distinct regions: the northern Negev (ca. 8,000 ha), the coastal plain (ca. 3,000 ha), the Khula valley in the north (ca. 150 ha) and the Arava valley in the south (ca. 100 ha). All potato fields are irrigated but the source of the irrigation water varies among the different production areas. Fresh water is used in the coastal plain and

the Khula valley, municipal recycled water in the northern Negev and saline water are used in the Arava valley. Late blight is the most destructive foliar pathogen of potatoes in Israel. Observations made in potato fields in the different regions suggested that the potential intensity of the disease differs in the different regions. Whereas severe epidemics occasionally develop in the coastal plain and the Khula valley, epidemics in the northern Negev are usually moderate and late blight seldom develops in potatoes grown in the Arava valley. Several factors (and their interactions) may create these differences. Among which are differences in production practices, microclimatic conditions and variation in the aggressiveness of the prevailing *P. infestans* isolates. However, as the different sources of the irrigation water coincide with the variable intensity of late blight epidemics in the different regions, it is possible that the source of the irrigation water plays a role in determining late blight intensity. The late blight simulator was applied to test this hypothesis.

The first step was to validate the late blight simulator was under Israeli conditions. Results of the validation efforts were presented in the first annual report. It was concluded that the late blight simulator developed in Cornell University provided satisfactory predictions of *P. infestans* epidemics in Israel, up to disease severity of 60%. This implies that the model can be used as a research tool for studying biological questions. The next step was to use the model for prediction of late blight intensity in the northern Negev region, where the fields are irrigated with municipal recycled water. Two trials were conducted for thus purpose in autumn of 2001. As in the previous trials, disease severity was assessed periodically from the date of disease onset until crop maturity and temperature and relative humidity were recorded within the potato canopy. The predicted epidemics were compared with those actually observed in field. Visual comparison of observed and simulated epidemics revealed that the predictions issued by the simulator overestimated the epidemics that actually developed in the fields (Figure 5). Comparing all observed and predicted epidemics corroborated these conclusions: the slope of the regression equation (1.34) was significantly higher than 1 (t-test; $P \leq 0.05$) (Figure 6).

Based on the findings described above we concluded that the development of late blight in fields irrigated with municipal recycled water is less severe than could be expected based on the suitability of the environmental conditions to the pathogen. Thus, it turns that some factor(s), which presumably is/are included in the recycled irrigation water, inhibit the rate of *P. infestans* development. In further studies it was found that Boron, a microelement that exists in high concentrations in recycled water, induces systemic acquired resistance against *P. infestans* and also against *Alternaria solani* (the causal agent of early blight).

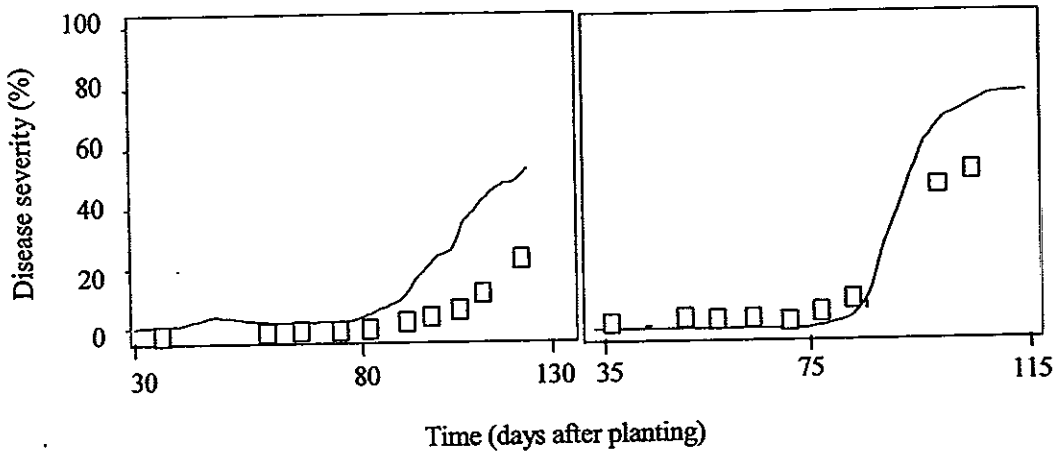

Figure 5. Using the late blight simulator developed in Cornell University to predict the severity of late blight epidemics in two field experiments conducted in autumn 2001. Both fields were located in the northern Negev and irrigated with municipal recycled water. Squares: observed disease severity in the field; line: simulated disease progress.

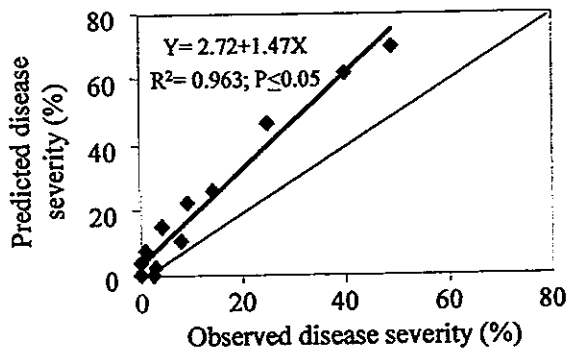

Figure 6. Comparison of late blight severity observed in four field experiments with the severities predicted by the Cornell late blight simulator. The 1:1 line is a theoretical line representing a perfect coincidence between observed and predicted values; the thick line represents the regression equation between observed and predicted values.

This study demonstrates the possibility of using computer simulation models as a research tool. The late blight simulator developed in Cornell University has been used for addressing biological questions in the last 20 years. However, it was used primarily in NY State. To the best of our knowledge, this is the first attempt to validate the simulator outside upstate NY. Our experience suggests that this particular simulator may be accurate, and thus, could be used as a research tool by researchers in other places and in other environments.

C. Scientific Impact of Collaboration

This year, collaboration was an important aspect of the project, both among the scientists directly involved in the project and with other scientists interested in the project. The scientists directly involved in the project used email, study visits and one meeting to facilitate collaboration. This year many of the specific modeling activities were transferred from Quito to the PhD student, Jorge Andrade, who is working at Cornell University in Ithaca NY. He will now focus on simulation as part of his PhD work. All this was done via email. The project scientists, including J. Andrade, met in Germany in July, 2002, to discuss project advances and plan future work. A report on the meeting was prepared D. Shtienberg and circulated. Also in 2002, Omer Frenkel, who had worked in the laboratory of D. Shtienberg, went to Quito for 3 months to participate on verification of the fungicide component of the simulator. Project scientists collaborated with scientists in the Netherlands (Wageningen), in the USA (USDA, Prosser, WA), Brazil, and a Norwegian researcher in Vietnam. All of these scientists have heard of the project and have offered to supply data sets for model validation.

D. Description of the Project Impact

We continued work reported last year with the field validation of late blight management strategies that are appropriate for resource poor farmers. In Ecuador this year, we had field trials on station and with farmers to test rainfall thresholds as simple decision support systems for farmers. Inexpensive rain gauges are used to measure rainfall, which is related to fungicide wash-off. Farmers use this information to decide whether or not to spray. These strategies were successfully tested in the field this year and gave promising results by significantly reducing the amount of fungicide used without increasing the risk of yield loss due to disease. Field validation has occurred always under similar conditions (similar altitudes). The simulator will be sued to evaluate how changes in weather conditions (especially temperature as a function of altitude) will affect the thresholds. This will facilitate application of the strategies to new environments.

E. Strengthening of Developing Country Institutions

Within the project we continued to work closely with the National Potato Program of Ecuador (INIAP). INIAP workers gained experience in field evaluation of the late blight management strategy, which includes data management and analysis. Although the simulator is not fully validated, it is still a useful tool for exploratory analysis of data. INIAP researchers also learned to do disease simulation using their data and the simulator. More

formal courses in disease simulation will be organized in the future, after the simulator has been adequately validated.

F. Future Work

This year we will validate the simulator with a large number of data sets. Preliminary work indicates that it will be applicable to diverse situation with certain restrictions. We will use the simulator to explore new management scenarios and design field validation trials. Using the simulator in this way will greatly increase the probably of success with the field trials. Because of new personnel in CIP, we will be able to repeat these field trials in 3 developing countries with a high degree of scientific rigor: Ecuador, Peru and Kenya. This year the Ecuadorian national program and CIP in Peru will validate general late blight strategies and specific decision support systems with farmers in the highlands of Ecuador and Peru. We will also gain new data sets for future model refinement from external collaborators in the US, Brazil and Vietnam. A structured simulation course will be given to the national program researchers in Ecuador.

Section II

A. Managerial Issues

There are no important managerial issues at this time.

B. Budget

No major changes have been made in the budjet.

C. Special concerns

No special concerns at this time.

D. Collaboration

The project scientists, including J. Andrade (a PhD student who is working at Cornell University in Ithaca NY on the simulation as part of his PhD work), met in Germany in July, 2002, to discuss project advances and plan future work. A report on the meeting was prepared D. Shtienberg and circulated. Also in 2002, Omer Frenkel, who had worked in the laboratory of D. Shtienberg, went to Quito for 3 months to participate on verification of the fungicide component of the simulator.

E. Request for American Embassy in Tel Aviv or A.I.D. Actions

No action is required at this time.

LATE BLIGHT

MANAGING THE GLOBAL THREAT

PROCEEDINGS OF THE GLOBAL INITIATIVE ON LATE BLIGHT CONFERENCE

HAMBURG, GERMANY
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IN CONJUNCTION WITH EAPR 2002, HAMBURG, GERMANY 14-19 JULY

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Using the Cornell late blight simulator to test biological questions: a case study on the influence of the source of irrigation water on *Phytophthora infestans* development

O Frenkel[1], D Shtienberg[1] and U Yirmiyahu[2]

Computer simulation models, if properly validated, can be used as research tools. The models can be used for testing biological hypotheses by conducting simulation experiments, reflecting "real-life" situations. To illustrate this approach, a computer simulation model, developed in Cornell University, was used. The model simulates the development of *Phytophthora infestans* (the causal agent of potato late blight) based on microclimatic data. Below, we will first describe the background and the biological question and hypothesis, and than, the experimental approach used to test the hypothesis.

Potatoes are grown in Israel in several distinct regions: the northern Negev (ca. 8,000 ha), the coastal plain (ca. 3,000 ha), the Khula valley in the north (ca. 150 ha) and the Arava valley in the south (ca. 100 ha). All potato fields are irrigated, but the source of the irrigation water varies among the different production areas. Fresh water is used in the coastal plain and the Khula valley, municipal recycled water in the northern Negev and saline water is used in the Arava valley. Late blight is the most destructive foliar pathogen of potatoes in Israel. Observations made in potato fields in the different regions suggested that the potential intensity of the disease differs in the different regions. Whereas severe epidemics occasionally develop in the coastal plain and the Khula valley, epidemics in the northern Negev are usually moderate and late blight seldom develops in potatoes grown in the Arava valley. Several factors (and their interactions) may create these differences, among which are differences in production practices, microclimatic conditions and variation in the aggressiveness of the prevailing *P. infestans* isolates. However, as the different sources of the irrigation water coincide with the variable intensity of late blight epidemics in the different regions, it is possible that the source of the irrigation water plays a role in determining late blight intensity.

To initially test if this possibility is relevant at all, late blight development over time was recorded in autumn 2001 in two potato fields located in the northern Negev. The fields were located at a distance of approximately 1 km apart from each other. One field was irrigated with fresh water whereas the other was irrigated with municipal recycled water. The fields were planted with the same potato cultivar and they were maintained (in respect to irrigation, fertilization, weed, pest and disease management, etc.) similarly. Late blight was observed in the field irrigated with recycled water about two weeks earlier, and the final severity of the disease in that field was higher than in the field irrigated with fresh water (Figure 1A). As the onset of the disease did not coincide in the two fields, a conclusive conclusion on the influence of the source of the irrigation water on the epidemic could not be obtained by comparing the actual disease severity values. Logit transformation of the percent disease severity values enabled to estimate the apparent infection rate (r) of the two epidemics. It was found that late blight developed significantly more rapidly in the field irrigated with fresh water than in the field irrigated with the municipal recycled water (Figure 1B). The apparent infection rate could have been affected by the source of the irrigation water, but also by microclimatic influences. Measurements of temperature and relative humidity in these two fields revealed that the differences between them were negligible (Figure 2). Thus, these data supports the hypothesis that the source of the irrigation water plays a role in late blight development and intensity.

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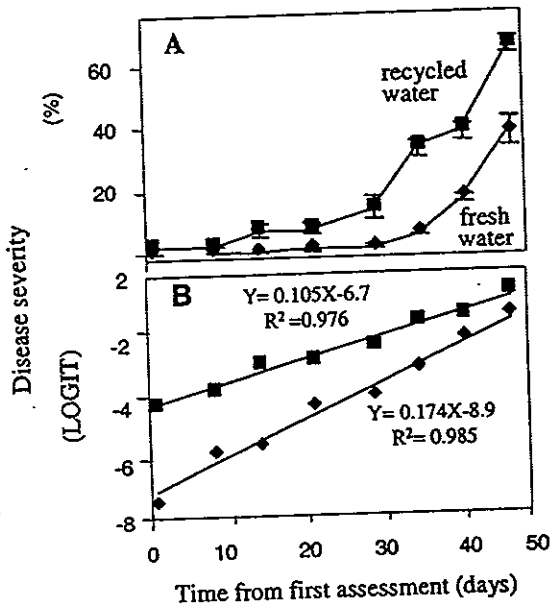

Figure 1. Effects of the source of the irrigation water on the development of potato late blight in fields irrigated with fresh water or with municipal recycled water. The vertical bars indicate the SE.

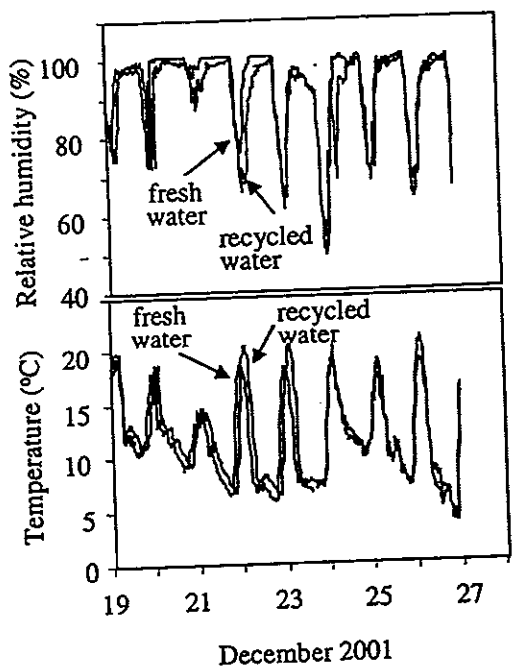

Figure 2. Changes in the relative humidity (A) and temperature (B) in a representative week as recorded within the canopy of two potato fields in autumn 2001. One field was irrigated with fresh water and the other with municipal recycled water.

Even if our conclusion based on these observations is correct and the source of the irrigation water affected late blight intensity in these two fields, it does not necessarily imply that this is one of the factors involved in the differences in late blight intensity between the different potato production areas. As the microclimatic conditions in the northern Negev are markedly different from those prevailing in the coastal plain, and since the microclimate governs late blight intensity, it would not be possible to exclude the influence of the microclimate from that of the source of the irrigation water. One possible way to differentiate between the two factors (and thus to expose the sole influence of the source of the irrigation water) is to take the effects of the microclimate into account in the analysis. This can be done by using the late blight simulator developed in Cornell University. The model was developed in the early 1980's by Bruhn and Fry (Bruhn and Fry, 1981; 1982a; 1982b) and it was revised and validated with independent data set in the early 1990's (Doster et al., 1990). The data used for validation was recorded in upstate New York, the region where the model's parameters were quantified. The validation efforts revealed the model accurately predicted late blight epidemics in that region. However, as the simulator was not yet validated under the local Israeli conditions, before using it for testing the role of the source of the irrigation water on late blight intensity, initial attempts should have been devoted for its validation.

The late blight simulator was validated under Israeli conditions using data recorded in four field trails. The trials were conducted in the coastal plain production area in the spring of 2001 and 2002. Each experiment consisted of plots not treated and plots treated with fungicides against *P. infestans*. In this report, results of the non-treated plots are presented. Disease severity was assessed periodically from the date of disease onset until crop maturity. Temperature and relative humidity recorded within the potato canopy by means of data-loggers were used to run the simulator. Then, predicted epidemics were compared with those actually observed in field. Visual comparison of observed and simulated epidemics revealed that the simulator reasonably predicted the epidemics that actually developed in the field in three out of the four experiments (Figure 3). However, visual comparison is a subjective, non-parametrical validation procedure. A more objective validation of the simulator could be achieved by statistical comparison of predicted vs. observed severities. This analysis suggested that the prediction ability of the simulator was high up to an observed severity of approximately 60%. Above that severity, the model generally under-estimated the actual disease severities and the variation of the differences between observed and predicted values was high (Figure 4A). When observed and predicted epidemics were compared up to disease severity of 60%, the predictions provided by the simulator were adequate. The intercept of the regression equation describing the coincidence between observed and predicted severities (0.4%) did not differ significantly from 0% and the slope of the regression equation (0.93) did not differ significantly (t- test; $P \leq 0.05$) from 1 (Figure 4B). Based on these findings we concluded that the late blight simulator developed in Cornell University provided satisfactory predictions of *P. infestans* epidemics in Israel, up to disease severity of 60%. This implies that the model can be used as a research tool for studying biological questions.

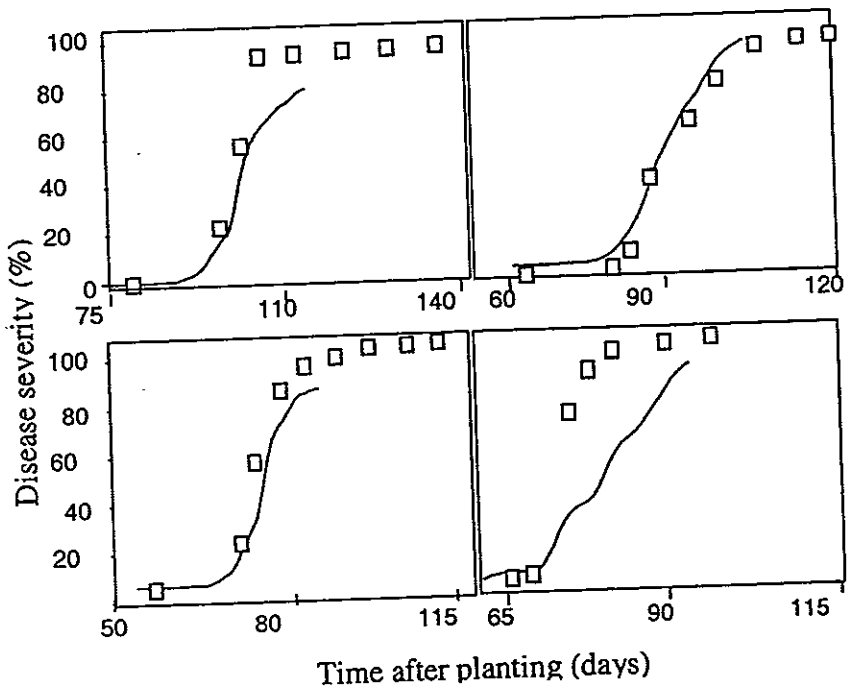

Figure 3. Using the late blight simulator developed in Cornell University to predict the severity of late blight epidemics in four field experiments. The experimental fields were located in the coastal plain of Israel and irrigated with fresh water. Squares: observed disease severity in the field; line: simulated disease progress.

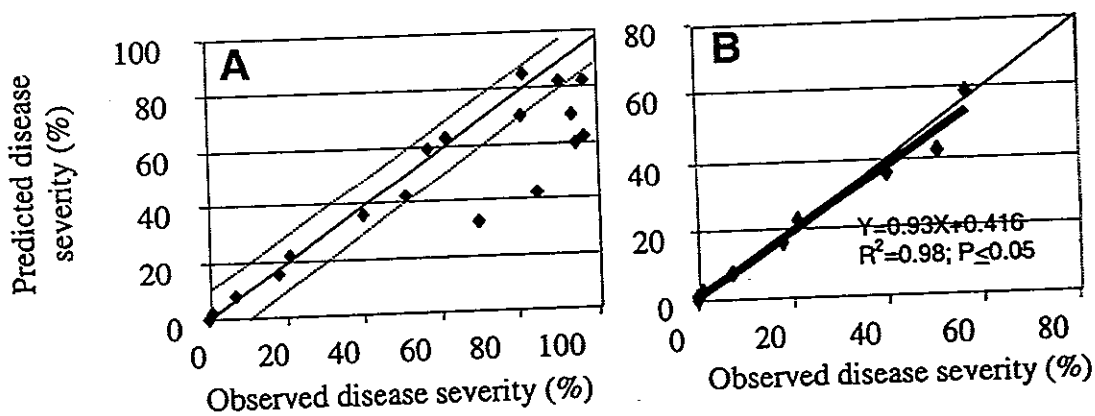

Figure 4. Comparison of late blight severity observed in four field experiments with the severities predicted by the Cornell late blight simulator. **A**: all data points recorded in the experiments; **B**: data points up to observed severity of 60%. The 1:1 line is a theoretical line representing a perfect coincidence between observed and predicted values; the dashed lines represents ± 10% of the 1:1 line; the thick line represents the regression equation between observed and predicted values.

The next step was to use the model for prediction of late blight intensity in the northern Negev region, where the fields are irrigated with municipal recycled water. Two trials were conducted for this purpose in autumn of 2001. As in the previous trials, disease severity was assessed periodically from the date of disease onset until crop maturity and temperature and relative humidity were recorded within the potato canopy. The predicted epidemics were compared with those actually observed in field. Visual comparison of observed and simulated epidemics revealed that the predictions issued by the simulator overestimated the epidemics that actually developed in the fields (Figure 5). Comparing all observed and predicted epidemics corroborated these conclusions: the slope of the regression equation (1.34) was significantly higher than 1 (t- test; $P \leq 0.05$) (Figure 6).

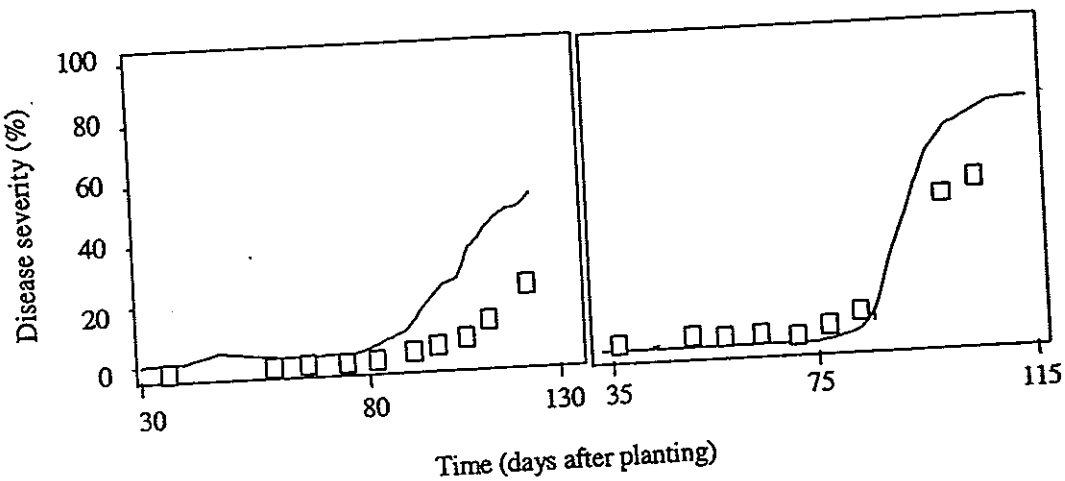

Figure 5. Using the late blight simulator developed in Cornell University to predict the severity of late blight epidemics in two field experiments conducted in autumn 2001. Both fields were located in the northern Negev and irrigated with municipal recycled water. Squares: observed disease severity in the field; line: simulated disease progress.

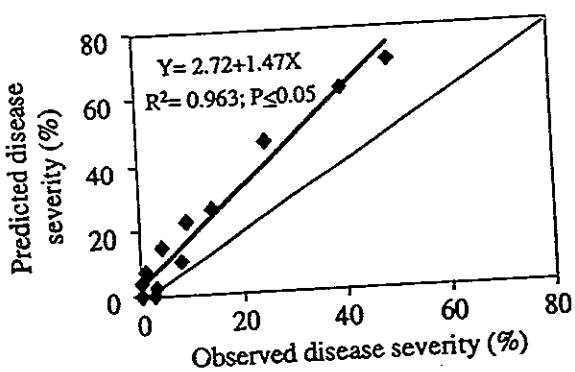

Figure 6. Comparison of late blight severity observed in four field experiments with the severities predicted by the Cornell late blight simulator. The 1:1 line is a theoretical line representing a perfect coincidence between observed and predicted values; the thick line represents the regression equation between observed and predicted values.

Concluding Remarks

Based on the findings described above we concluded that the development of late blight in fields irrigated with municipal recycled water is less severe than could be expected based on the suitability of the environmental conditions to the pathogen. Thus, it turns that some factor(s), which presumably is/are included in the recycled irrigation water, inhibit the rate of *P. infestans* development. In further studies it was found that Boron, a microelement that exists in high concentrations in recycled water, induces systemic acquired resistance against *P. infestans* and also against *Alternaria solani* (the causal agent of early blight).

This study demonstrates the possibility of using computer simulation models as a research tool. The late blight simulator developed in Cornell University has been used for addressing biological questions in the last 20 years. However, it was used primarily in New York State. To the best of our knowledge, this is the first attempt to validate the simulator outside upstate New York. Our experience suggests that this particular simulator may be accurate, and thus, could be used as a research tool by researchers in other places and in other environments.

Acknowledgments

This research was supported in part by under Grant No. TA-MOU-99-C15-073 US – Israel Cooperative Development Research Program. This project is conducted in collaboration with G A Forbes from CIP, Quito Ecuador[1] and W E Fry from Cornell University, Ithaca, New York, USA.

Literature cited

Bruhn J A and Fry W E. 1981. Analysis of potato late blight epidemiology by simulation modeling. Phytopathology 71:612–616.

Bruhn J A, and Fry W E. 1982a. A statistical model of fungicide deposition on potato foliage. Phytopathology 72:1301–1305.

Bruhn J A, and Fry W E. 1982b. A mathematical model of the spatial and temporal dynamics of chlorothallonil residues on potato foliage. Phytopathology 72:1306–1312.

Doster M A, Milgroom M G and Fry W E. 1990. Quantification of factors influencing potato late blight suppression and selection for metalaxyl resistance in *Phytophthora infestans*: A simulation approach. Phytopathology 80:1190–1198.

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Towards an integrated and universal crop-disease model for potato late blight

Rubí Raymundo[1,2], Jorge Andrade[3], Henry Juarez[1], Greg Forbes[1] and Robert J. Hijmans[3,4]

Potato late blight, caused by *Phytophthora infestans*, is an important and relatively well-studied crop disease system. Nevertheless, research is needed to predict or manage its incidence and severity. Along with other factors, such as changing pathogen populations, late blight is highly dependent on the weather, which makes the disease highly variable in space and time (Hijmans et al., 1999).

Simulation modeling could be used to integrate epidemiological knowledge about *P. infestans* and to improve disease management, breeding programs, and research impact assessment.Late blight was one of the first crop diseases for which a weather driven dynamic simulation model was developed (Waggoner 1968). Bruhn and Fry (1981) developed a similar model that was further modified by subsequent workers at Cornell University (here referred to as the "Cornell model"). This model simulates the effect of temperature and humidity on the various stages of the life cycle of *Phytophthora infestans* (infection, latency, lesion growth, sporulation). It was parameterized using data from detailed laboratory experiments by Crosier (1934).

Subsequently, Michaelides (1991) and Van Haren and Janssen (1999) developed somewhat different alternative models. Van Oijen (1991) also developed simulation models for potato late blight, but these were not weather driven (but could be used to compare between treatments (cultivars) grown at the same site). Van Haren (1999) incorporated some of Van Oijen's work into the first coupled host (potato) – pathogen model. They used an elaborate version of the LINTUL potato model that takes different leaf layers into account. Their approach involved new approaches to model fungicide weathering. All the above models have a daily time step.

The dynamic simulation models mentioned above should be clearly distinguished from disease forecast models such as Blitecast (Krause et al., 1975). Disease forecast models are typically empirical models that can be useful to manage the disease by helping determine the optimal onset and intervals of fungicide sprays. They do not estimate disease severity over time or yield. Neither can they be easily adapted for different cultivars. Also, they are more likely to have a limited geographic domain of validity, as illustrated by the number of different forecast models for different regions. Dynamic simulation models could be an effective basis for the development of forecasters (Fry et al., 1983).

We have been using the Cornell model to attempt to simulate late blight in the tropical highlands of the Andes (Forbes et al., 2001) and elsewhere, but have had mixed results, particularly in simulating the effect of fungicides (Andrade, 2000). Therefore we have embarked on a series of field and lab experiments to further develop and calibrate this model using the following criteria:

- The model should be universally valid (or there should be clearly defined geographic domains for certain versions).
- The model should make biological sense (based on knowledge of sub-systems) so that it is more likely to be generally valid, it can be easily understood, and it can be improved with new knowledge.
- Where possible, cultivar specific parameters should be measured. (and not calibrated as was done by the workers in Cornell). This is particularly important for our objective of supporting a breeding program.
- The model should estimate yield through coupling with a potato growth simulation model.

In this paper we report some preliminary results from this work. We first describe some basic epidemiological work on the leaflet/plant scale. We then discuss reasons for changing the time step of the model from daily to hourly. Finally we describe the way we integrated the disease model with a potato growth model.

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Components of resistance

In the Cornell model, the life cycle of *P. infestans* is modeled using (cultivar dependent) parameters for components of resistance. These components are infection efficiency, latency period, lesion growth rate, and sporulation intensity. The (fixed) value of these parameters is multiplied with a climate dependent factor (different for each day, and for each component) between 0 and 1. These climate dependent factors are derived from the temperature and humidity of that day. In the aforementioned studies with the Cornell model, the components of resistance were not measured, but estimated through calibration of field experiments. In some cases this seems to have yielded unrealistic values, but apparently this did not affect the results because they were compensated by other parameters. The objective was typically to compare fungicide treatments, and to a lesser extent differences between cultivars. The model was not used outside the (geographic/ecological) domain of development. For our intended purposes, including the use of the model for areas that are distant from each other and the comparison of different genotypes, the calibration of these parameters would not appear to be a viable option.

This approach of a fixed parameter and a changing environmental modifier has a number of important implications/assumptions. In the first place, the cultivar-dependent parameters should be measured the optimal temperature (e.g., at around 21°C for latency period; Figure 1) or else their values should be adjusted before they are used in this type of model (or used for comparison). More generally, data on latency period and other components of resistance should always be published together with the temperature and humidity conditions during the experiment. This is currently not always done, and that makes these values incomparable across experiments (except perhaps, where there are common cultivars across experiments that could be used for scaling).

This approach also assumes that the components of resistance are independent of other factors such as the life cycle of the plant. However, there are observations of changing levels of resistance during the life cycle related to leaf age (Visker et al., 1998), and also due to other factors such as N content of the tissue (Juarez and Hijmans, 2002). Models could be relatively easily adjusted for changes in the components due to these factors, but more data are needed to further confirm and quantify the relationships.

Another important assumption is that these parameters are constant during the life cycle of one lesion. This may not be true, and have serious implications for the comparability of different experimental results (see sections below).

Whichever the reason, there are differences between measurements of components. This is illustrated by Table 1, in which three components are compared for two cultivars, as determined by three different workers. The differences in sporulation capacity are astonishing, but the differences in latency period are also up to 50% between experiments (whereas within experimental variation is typically much smaller).

Table 1. Differences in reported values of components of resistance in two cultivars, respectively by Andrade (2001), Juarez (unpublished) and Raymundo (unpublished).

Cultivar	Latency Period (hours)		
Amarilis	90	96	104
Tomasa	82	79	90
	Lesion growth rate (mm/day)		
Amarilis	4.5	3.0	3.1
Tomasa	5.5	3.6	4.0
	Sporulation capacity (spore.mm²/day)		
Amarilis	29	88	31
Tomasa	92	210	73

Latency period. In the Cornell model latency period was the only variable that was not dependent on the weather. It was modeled as a fixed number of days. We have added a function to simulate the effect of temperature on latency period. We used laboratory experiments and data from other workers to derive two simple linear relationships with an optimum temperature at 21°C (Figure 1; Andrade, 2000). Because of the very strong relation between temperature and latency period this appears to be a very important addition to the model.

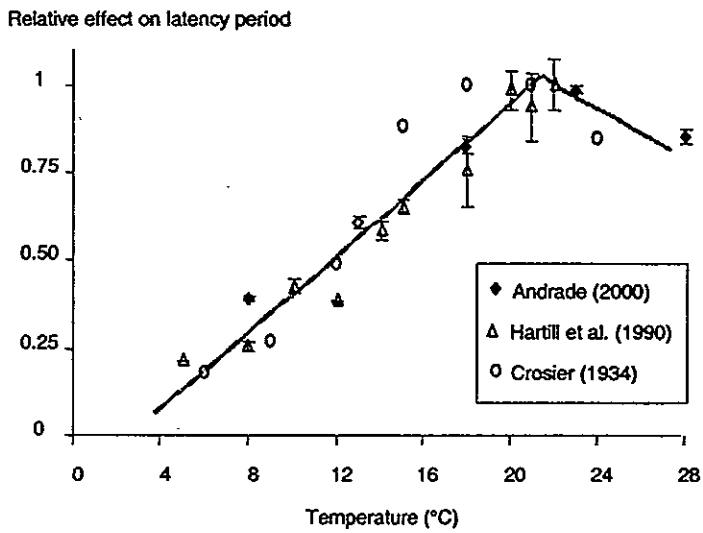

Figure 1. Relative effect of temperature on latency period. Observations from three experiments and a tentative generalization (line). Source: Andrade (2000).

Lesion growth rate. The effect of temperature on lesion growth rate was changed according to Figure 2. Note that recent experimental data, as in the case of latency period (Figure 1) largely conform Crosier's (1934) data, except for his data points at 25 and 30°C. The equation in the model was changed to better accommodate the effects of very low and very high temperatures (i.e., outside of the range of temperatures of the area for which the model was originally developed).

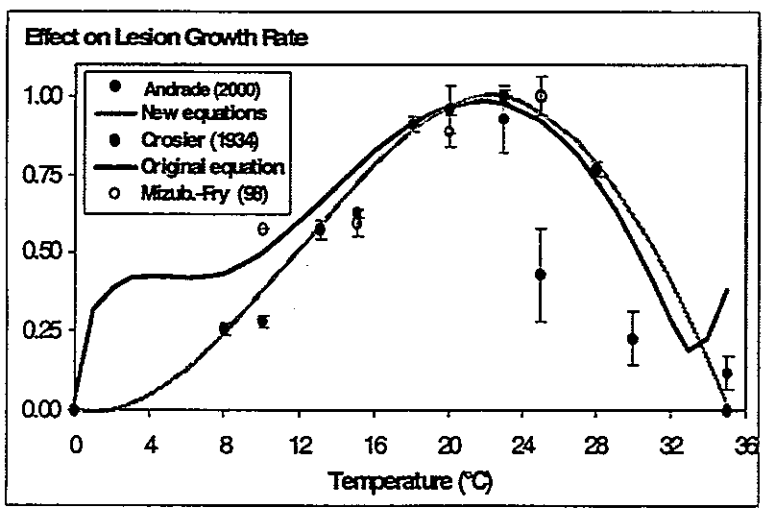

Figure 2. Effect of temperature on lesion growth rate.

With a series of Petri dish experiments on detached leaflets, we tested whether lesion growth rate was constant over time. Lesion size (expressed in mm^2) increases over time with a logistic (S-shaped) curve. However, lesion growth rate is fairly constant when expressed as the increase of the radius of the lesion over time (mm/day), at least until the border of a leaflet is reached (Figure 3; Raymundo, unpublished). Therefore, lesion size is less useful to report.

Lesion growth rate is not highly sensitive to small changes in experimental protocol (such as the time lapsed between inoculation and measurement of lesion area). However, care should be taken that the lesion area is not measured too late (after the lesion has reached the limits of the leaflet). This is because the radius of the lesion is usually not measured since a lesion is not a perfect circle. The lesion area is measured and the radius estimated from that measurement.

We did find evidence for cultivar-dependent, reduced lesion growth in dry circumstances (Figure 4; Raymundo, unpublished). In this experiment leaflets were inoculated in vitro (detached in Petri dishes), in greenhouse (humid) and in a nethouse (dry). The temperature regime was comparable across the three environments. Experiments to determine this component of resistance are generally carried out under very humid circumstances and will perhaps not be affected. It would be important to further quantify this effect and perhaps incorporate it in the model. The effect was greater for the most resistant of three varieties. This interaction is worrisome, as it could preclude easy modeling of this phenomenon when it happens in some cultivars, but not in all, or at different thresholds.

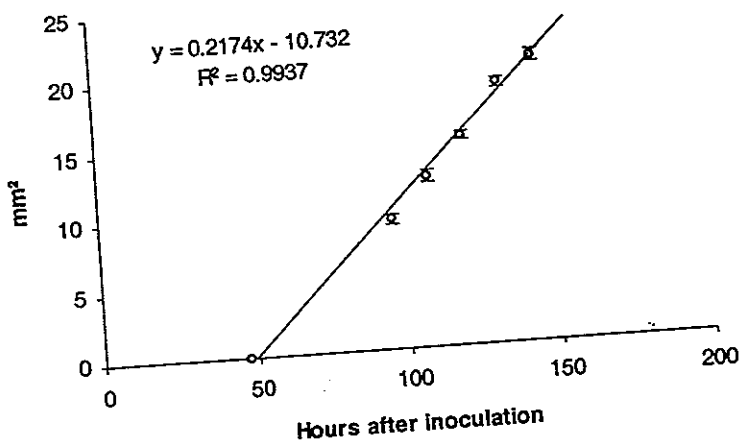

Figure 3. Lesion growth rate as expressed as the increase of the radius of the lesion over time (mm/day).

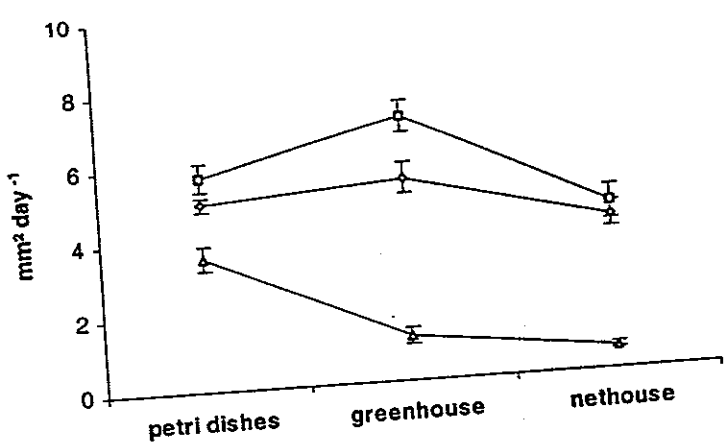

Figure 4. Lesion growth rate in three environments (mm/day).

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Sporulation rate. Sporulation rate, as it calculated following standard protocols, is highly sensitive to the time lapsed between latency and the moment of measurement. It appears that the sporulation rate increases. This can be due to continuous sporulation of all the tissue. In the currently used equation it is implicitly assumed that all infected tissue only sporulates during one day. Even after changing that to ongoing sporulation on all tissue we still did not come close to getting a constant rate. This implies that reported sporulation data in the literature might not be comparable at all (in addition to the other problem of measurements under different environmental conditions, as mentioned above). We have not resolved this issue, nor its implications for modeling.

Hourly time steps

There is a need for hourly time steps because the temperature curves have optima. Thus a reading of the average temperature may be rather different from the average of the hourly values.

Another complication is the temporal dynamics during the day of sporulation and infection. Our preliminary data from Huancayo show a somewhat consistent pattern of a peak in spore release during the morning hours (based on rotorod spore trap sampling), as commonly reported, but infection occurring during the afternoon (based on trap plants). Total spore production is not only a function of infected leaf area (as in the model), but also of healthy leaf area.

Host growth

We have coupled the LINTUL model to the Cornell disease model. LINTUL is a simple general crop model. Dry matter production is simulated as the result of light interception and utilization with a constant light use efficiency. LINTUL simulates potential crop growth, but extensions of the model dealing with drought, potato late blight and potato cyst nematodes have been developed already (Van Oijen et al., 1995; Van Oijen, 1991). The model coupling is in two processes: (1) crop growth influences the fraction of the spores that land on green leaves (or are lost) and (2) lesion growth diminishes leaf area, and hence production.

A problem in validating the model has been that it can be difficult to interpret the common "% severity" because it means percent of the currently present foliage, not of the total foliage that would have otherwise been present (which is calculated with a model)

Conclusions

Progress has been made, but there is a long way to go. The following activities require attention:

- Measuring the initial inoculum
- Improving the fungicide submodel
- Verifying the estimation of leaf wetness period
- Verifying if sporulation rate is constant

Changes in the pathogen population will greatly complicate the use of the model for many different environments. Although the Latency period, Lesion growth rate and Sporulation rate are commonly referred to as components of resistance, it might be better to refer to them as components of interaction because they are genetically controlled by the host (components of resistance) and by the pathogen (components of pathogenicity) —Together these make components of interaction.

Literature cited

Andrade-Piedra Naranjo J L. 2000. Epidemiología del tizón tardío de la papa en los Andes peruanos: Validación del simulador LATEBLIGHT. Magister Scientiae Thesis, Universidad Nacional Agraria La Molina. 149 pp.

Bruhn J A. and Fry W E. 1981. Analysis of potato late blight epidemiology by simulation modeling. Phytopathology 71:612–616.

Crosier W. 1934. Studies in the biology of *Phytophthora infestans* (Mont). de Bary. Cornell U. Agr. Exp. Sta. Memoir 155:1–40.

Fry W E, Apple A E, Bruhn J A. 1983. Evaluation of potato late blight forecasts modified to incorporate host resistance and fungicide weathering. Phytopathology 73, 1054–1059.

Forbes G A, Chacón G, Taipe M and Hijmans R J. 2001. pp 87–93 in: Simulating potato late blight in the highland tropics. Scientist and Farmer, Partners in Research fo rthe 21st Century. Program Report 1999–2000. International Potato Center. Lima, Peru.

Hijmans R J, Forbes G A and Walker T S. 2000. Estimating the global severity of potato late blight with GIS-linked disease forecast models. Plant Pathology 49:697–705.

Juárez H S, Amaro J R, Rivera M D, Párraga A and Hijmans R J. 2002a. Efecto del nitrógeno en el tizón tardío de la papa. pp. 121–132 in: Fernández-Northcote E N (ed), Memorias del taller internacional Complementando la Resistencia al Tizón (*Phytophthora infestans*) en los Andes, Febrero 13–16, 2001, Cochabamba, Bolivia, GILB,Taller Latinoamérica 1. International Potato Center, Lima, Peru.

Juárez H S, Avila L M and Hijmans R J. 2002b. Modelos de predicción del tizón tardío y el programa CASTOR 2.0. pp. 157–162 in: Fernández-Northcote E N (ed), Memorias del taller internacional Complementando la Resistencia al Tizón (*Phytophthora infestans*) en los Andes, Febrero 13–16, 2001, Cochabamba, Bolivia, GILB,Taller Latinoamérica 1. International Potato Center, Lima, Peru.

Krause R A, Masie L B, Hyre R A. 1975. Blitecast: a computerized forecast of potato late blight. Plant Disease Reporter 59:95–98.

Michaelides S C. 1991. A dynamic model of the interactions between the potato crop and Phytophthora infestans. Bulletin OEPP/EPPO Bulletin (France).

Van Haren R J F. 1999. The LINTUL late blight active layer model. Proceedings of The Third International Symposium on Systems Approaches for Agricultural Development, Lima, Peru, 8–10 November 1999.

Van Oijen M. 1991. Identification of the major characteristics of potato cultivars which affect yield loss caused by late blight. Ph.D. Thesis, Agricultural University. 116 pp.

Van Oijen M, de Ruijter F J and Van Haren R J F. 1995. Modelling the interaction between potato crops and cyst nematodes. pp. 185-196 in: Haverkort A J and MacKerrow D K L (eds), Potato ecology and modelling of crops under conditions limiting growth. Kluwer, Dordrecht.

Visker, M. H. P. W., Colon, L. T., and Struik, P. C. 1998. The relationship between maturity and resistance to late blight (*Phytophthora infestans*) in potato (*Solanum tuberosum*). Potato Research. 41:198–199.

Waggoner P E. 1968. Weather and the rise and fall of fungi. In: Biometeorology (ed, P. Lowry), pp. 45-66.

Simulation in Diverse Environments

G A Forbes[1], M V Taipe[2], P J Oyarzun[3], R J Hijmans[1]

This paper describes a collaborative effort that began several years ago and was subsequently formalized by a USAID-funded project that started in 2001. The objective of the collaborative effort is to design location-specific late blight management strategies for resource-poor farmers in less developed countries (LDCs). The more specific objective of the USAID-funded project is to use computer-aided disease simulation to assist in the development of late blight management strategies in LDCs. Many people have contributed significantly to the late blight management effort. This paper, however, deals more specifically with the simulation project, and those collaborating directly in this project are P J Oyarzun and M V Taipe (Ecuador), W E Fry and J L Andrade (USA), R J Hijmans and G A Forbes (Peru), B Kassa (Ethiopia), O M Olanya (Kenya), and E S G Mizubuti (Brazil).

The simulation project is designed to follow a logical sequence of events, with some degree of reiteration (Figure 1). The first part of the project is aimed at collecting data from experiments in different parts of the world. Subsequently, these data will be used to validate a late blight simulator developed at Cornell Univ. (Bruhn and Fry, 1981). Then follows a period of model adjustment and revalidation. Finally, the model will be used to examine real-life disease management strategies. Although this process is basically sequential, new experiments and data acquisition are still underway, although at a reduced pace.

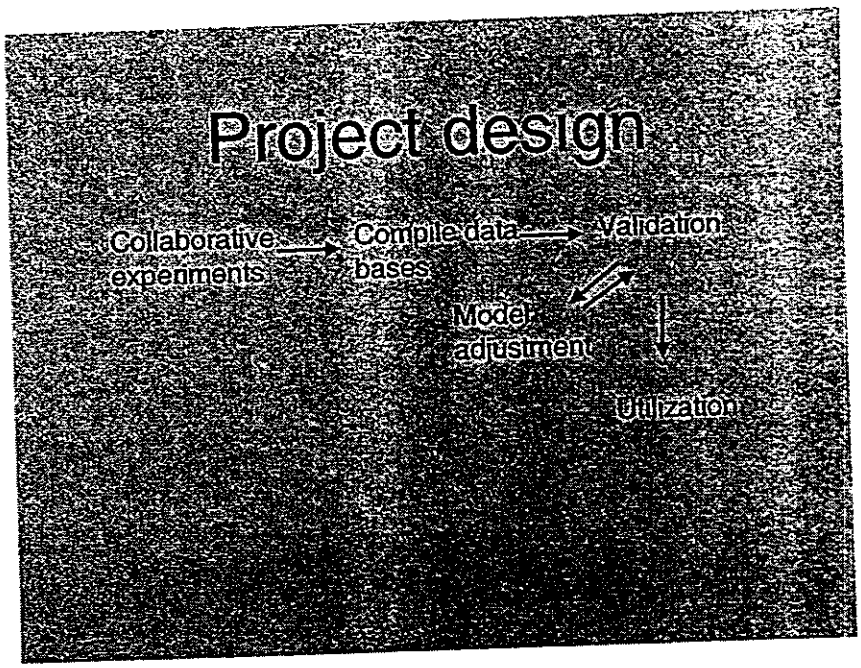

Figure 1. Schematic diagram of logical sequence of steps followed in late blight simulation project. Validation and model adjustment are a reiterative process.

Development of data system for experimental data

This is not really a single database of experimental data, but rather a system of different databases (Figure 2). The methodology for this activity is straightforward. Data from experiments of collaborators are entered into the database using a set of guidelines that was modified from other simulation efforts. All the data are

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currently in SAS data files and all descriptive information is in MSWord files. At this time, descriptive information is available only in Spanish.

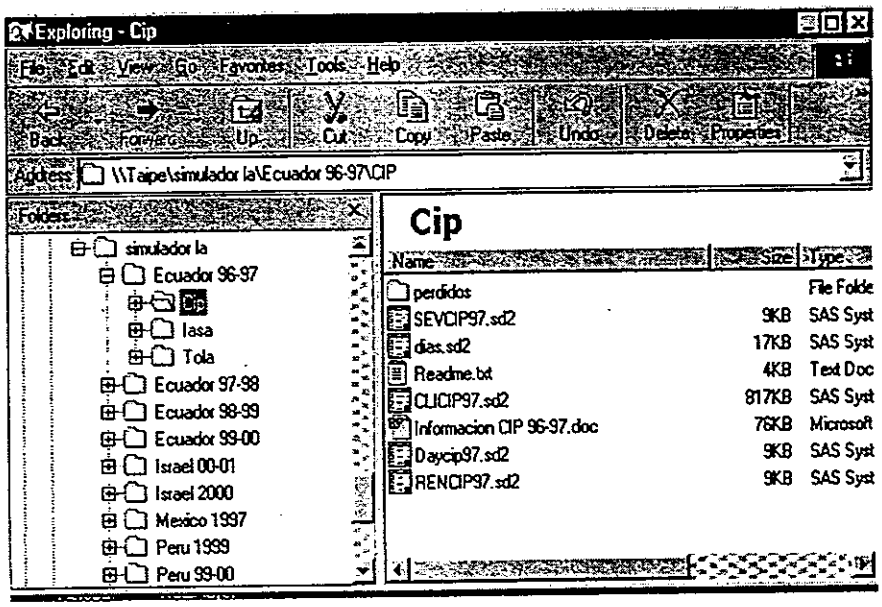

Figure 2. Image of file structure of data system of experimental data used in simulation.

To date the data system contains information and data from 25 different experiments (Table 1). Countries represented include Ecuador, Peru, Ethiopia, Mexico Israel, Brazil and the USA. In 2002 and 2003, we anticipate getting information from the USA, Peru, Ecuador, Brazil and Vietnam. All information is in a format ready to be used for simulation.

Table 1. Number and location of data sets appropriate for simulation of potato late blight.

Location	Years	Trials
Ecuador	1996–2000	10
Peru	1999–2000	4
USA	1998–2001	3
Brazil	2000	1
Israel	2000–2001	6
Mexico	1997	1
Total		25

Improvement of simulation model – use of Vapor Pressure Deficit (VPD).

The simulation model uses relative humidity (RH) of 90% as proxy for leaf wetness. At a RH of 90% and a temperature of 20° C, the VPD is 0.235 kPa. At lower temperatures, the same VPD occurs at lower RH levels (Figure 3). For this reason we compared simulations of weather data from different sites using leaf wetness estimated by RH at 90% with simulations at the same sites using leaf wetness estimated by a VPD of 0.235 kPa.

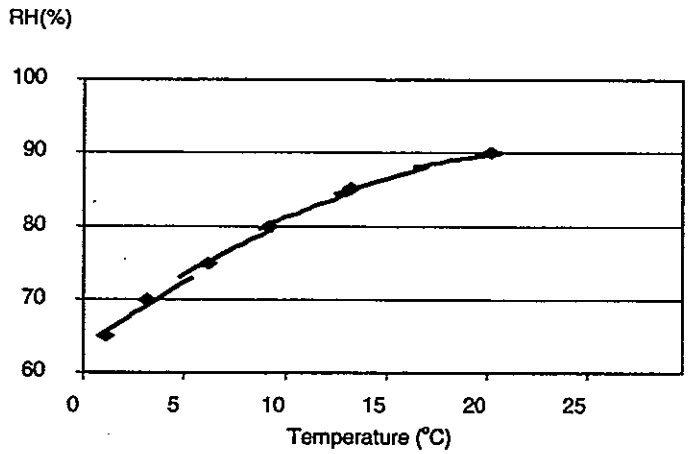

Figure 3. Temperature and relative humidity (RH) values for a VPD of 0.235 kPa.

Here we present some preliminary results of these simulations. First, it appears that the use of VPD generally improves the predictive ability of the simulator. This is more evident with susceptible cultivars (Figure 4) than with resistant cultivars (not shown). The reduced affect of VPD with resistant cultivars is somewhat an artifact due to low disease severity. Because the relation between RH and VPD is temperature dependent (Figure 3), effects are greater at low temperatures (Figure 4) where resistant cultivars often have very little infection. Generally, VPD seems to be a superior parameter for estimating leaf wetness at low temperatures. The fact that VPD and RH estimate leaf wetness similarly at higher temperatures is evident in our results (Figure 4). We are now in the process of more exhaustive analyses to confirm the utility of this parameter.

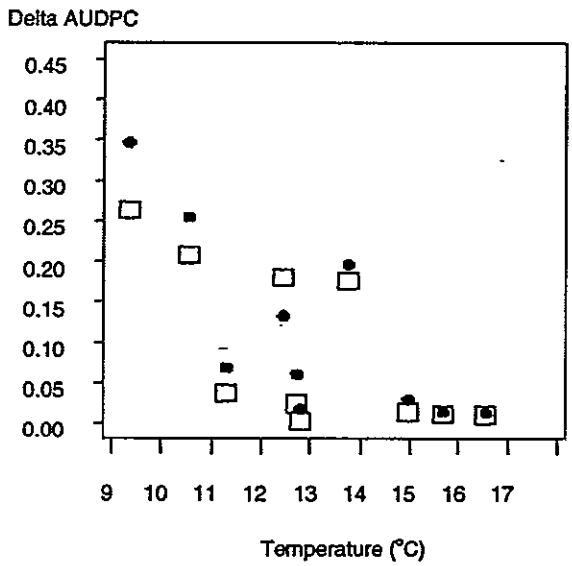

Figure 4. Relation between temperature and difference in AUDPC (Delta AUDPC between simulations using RH (solid squares) and simulations using VPD (open squares). Data are from the simulation of disease in a susceptible cultivar. RH = relative humidity, AUDPC = area under the disease progress curve.

Implementation of model in theoretical applications – disease severity in Ethiopia

In the study we used the simulator to explore factors affecting disease severity in Ethiopia. Weather data (hourly temperature and relative humidity) were taken from several sites (Figure 5). Simulations were run using these weather data, but all other parameters (cultivar resistance, disease initiation) were the same. Therefore, this exercise indicates the effect of local weather parameters on disease severity.

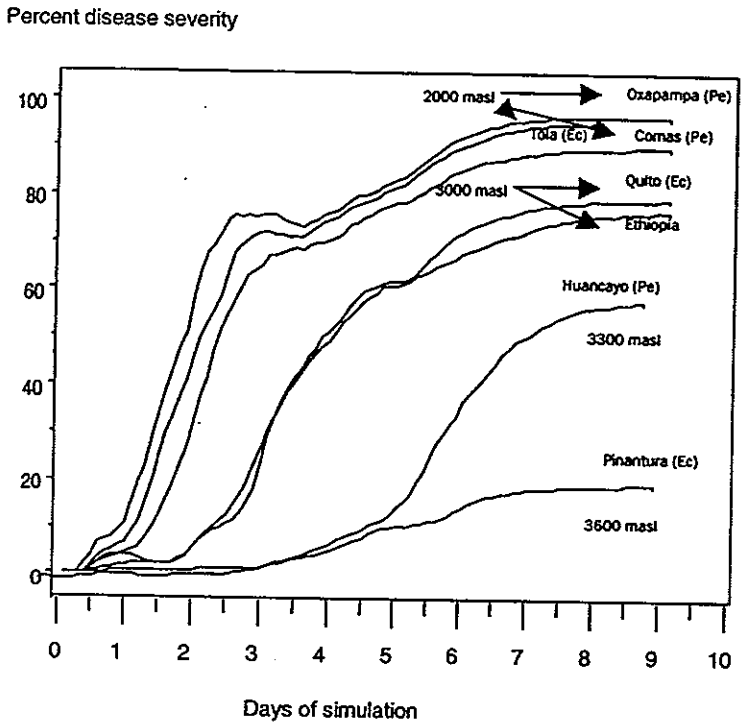

Figure 5. Disease progress curves for several international sites. Note that Ethiopia and Quito have similar severity levels and both are at 3000 meters above sea level. Ec=Ecuador, Pe=Peru

All sites were then classified based on potential disease severity. Ginchi, Ethiopia, was classified similar to Quito Ecuador (both are at about 3000 masl). However, in Ginchi, national potato program workers regularly protect materials from blight with one well-timed spray of the systemic fungicide metalaxyl (formulated in combination with a protectant fungicide). This seems almost impossible for Quito where even resistant materials require 4 to 5 sprays. Therefore, we hypothesize that factors other than weather are involved. For example, most farmers plant in the dry season in Ginchi when disease pressure is low. When the national program plants during the rainy season, there are not many other potatoes in the areas. Aerial inoculum is probably reduced. Should these factors change in Ethiopia, late blight could become more severe, and the current fungicide strategy would not work.

Implementation of simulator and development of practical management strategies – the case of rainfall thresholds.

One of the principle problems with contact fungicides is that they are washed of with rain. Systemic fungicides do not wash off but small amounts of systemic fungicide are generally formulated with larger amounts of protectant fungicide. For this reason, a large part of the commercial product is lost in rain.

The amount of fungicide needed to protect a potato plant depends on the level of host plant resistance in that particular cultivar and on the environmental conditions. Highly resistant plants require less fungicide, as do plants growing in conditions less favorable to the development of the disease. At this time, however, no potato cultivar has sufficient resistance and for that reason some amount of fungicide must always be used when conditions are favorable for disease development.

One of the most difficult aspects of fungicide usage in the control of potato late blight is determining the correct time for application. In the industrialized countries, farmers have access to highly sophisticated decision support systems (DSS), which provide guidelines for timing of fungicide sprays. These systems, which require significant inputs, are not available to resource-poor farmers. For this reason, CIP and partners have been exploring the possibility of developing simple DSS for resource-poor farmers based on rainfall, which is an environmental parameter that these farmers can measure.

Based on some published research done in Colombia (Castaño and Thurston, 1968) and empirical studies, CIP had determined levels of rainfall that would represent dangerous levels of fungicide wash-off for cultivars of different levels of resistance. A hypothesis was developed stating that plants would be unprotected after 10, 18 and 30 mm of rainfall for a susceptible, moderately resistant and resistant cultivar, respectively. This hypothesis was tested in 2001 and 2002 in three locations in Ecuador, one on the CIP experiment station and two on farmer's fields, one in the province of Chimborazo and one in the province of Cañar.

Experimental design

In each case, rainfall was measured with a rain gauge. At CIP, this was done with automated weather equipment. At the two other locations, rain was measured with inexpensive gauges that can be constructed with disposable water bottles and funnels (Figure 6). In Chimborazo and Cañar, the three rainfall thresholds were compared with a control based on what local farmers do. Each threshold was applied only to the cultivar for which it is hypothesized. At CIP, the thresholds were applied to all cultivars (resistant, moderately resistant and susceptible) and compared with weekly and unsprayed controls. In order to avoid daily sprays, should a threshold be reached two or more days consecutively, minimum applications periods were employed. These were 5 days for the susceptible cultivar, 7 for the moderately resistant and 10 for the resistant.

Figure 6. Ecuadorian potato worker showing farmers how to make water-bottle rainfall gauge.

Results

CIP The thresholds worked very well for the resistant cultivar, including the 30-mm threshold, which required the least number of sprays (Table 2). Disease was controlled well with all treatments except the unsprayed treatment. With the 30-mm threshold, disease started to increase at the end of the season, but this was at about 100 days after planting. This resistant cultivar has a short maturity period and the plant would be in senescence after 100 days. Host plant resistance often begins to break down when a plant begins to senesce. Nonetheless, late blight at this point would have little effect on yield.

Several treatments did not control the disease very well in with moderately resistant cultivar (Table 2). The unsprayed and 30 mm treatments were severely infected at 100 days. The other three treatments (18 mm, 10 mm and weekly) were similar, and in each case disease severity was rising near 10 % at 100 days. The moderately resistant cultivar does not mature as quickly as does the resistant, and disease at 100 days after plant can cause yield losses.

No treatments worked sufficiently well with the susceptible cultivar (Table 2). The 10 mm and weekly treatments gave the best control, but still disease was near 20 % at 100 days. This cultivar is the longest maturing of the three and would suffer yield loss with disease at 100 days after planting.

Table 2. Level of control of different treatments designed to assist farmers in timing fungicide sprays for control of potato late blight (results from experiment at CIP only).

Treatment[a]	No Sprays	Cost USD	Control level[a]		
			Resistant	Mod. Resis.	Susceptible
Weekly	11	330	Good	Partial	Partial
10 mm	12	360	Good	Partial	Partial
18 mm	8	240	Good	Partial	Bad
30 mm	5	150	Good	Bad	Bad
Unsprayed			Bad	Bad	Bad

[a]Sprays were made either weekly or after the indicated amount of rainfall had fallen. Treatments that maintained disease to about 10% until 100 days after planting were considered to give good control, while those maintaining disease to 20% were considered to give partial control.

Chimborazo and Cañar. At the time of this writing, experiments in these sites have terminated, but data are still being processed. Nonetheless, preliminary examination data indicates that the 30 mm threshold worked well for the resistant cultivar, but the other thresholds were not nearly as useful for managing the disease in the moderately resistant (18 mm) and susceptible cultivars.

Literature cited:

Bruhn J A and Fry W E. 1981. Analysis of potato late blight epidemiology by simulation modeling. Phytopathology 71:612–616.

Castaño J J and Thurston H D. 1968. Control de la "Gota" en tomate. Aspersion de maneb en tomate a distinctos intervalos semenales y niveles de lluvia para controlar Phytophthora infestans. Agricultura Tropical 24:262–264.