ESTIMATING YIELD LOSS IN POTATO DUE TO BACTERIAL WILT CAUSED BY *PSEUDOMONAS SOLANACEARUM*

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ABSTRACT

Bacterial wilt or brown rot, caused by *Pseudomonas solanacearum* E.F. Smith, severely limits potato production in warm growing areas of the world. Accurate quantification of yield loss has not been determined. Subjective estimates of losses at international, national and regional levels have been determined from statements of authority, postal or on-farm inquiries and surveys of disease intensity. Specific field experiments, conducted in inoculated and uninoculated soils for several sites and seasons, would provide the more detailed information required to generate regression models which relate disease intensity and yield loss. Methodology for assessment of disease intensity and marketable yield may be adapted from procedures used to screen potato genotypes for resistances to the diseases in the field. Analysis of data from screening experiments indicated linear relationships between yield loss and disease intensity as well as between plant wilt and tuber rot intensities. Multiple regression analysis showed that yield loss per unit increase of disease intensity was similar in three experiments conducted in different years and countries.

Introduction

As potato production continues to expand rapidly in tropical, sub-tropical and warm-temperate areas of the world, bacterial wilt caused by Races 1 and 3 of *P. solanacearum* E.F Smith has become recognized as one of the most serious factors limiting production (French, 1979). The symptoms and epidemiology of the disease have been defined previously (Kelman, 1981; Martin and French, 1985). Although much is known of the distribution of the pathogen worldwide (Kelman, 1953; French, 1979; International Potato Center, 1984; Persley, 1986), accurate quantification of yield loss and its relationship to bacterial wilt intensity in the field have not been determined. Therefore, information to date is mostly subjective, based on expert opinion, growers' experience and surveys of disease intensity.

The following describes the types of loss caused by *P. solanacearum* on potato and reviews current practices to determine disease intensity and assess losses. Methodology for more detailed quantification of yield loss due to bacterial wilt is also proposed. In this paper, aerial symptoms will be referred to as bacterial wilt, whereas, tuber symptoms will be referred to as brown rot.

Losses caused by *P. solanacearum*

Direct losses which reduce quantity, quality or production capacity, may be primary or secondary (Zadoks and Schein, 1979). Primary losses take place during the growing season or storage period, whereas, secondary losses are due to effects on the yielding capacity of subsequent crops. Both kinds of direct loss are caused by *P. solanacearum*. Indirect losses, which encompass economic and social effects beyond the agricultural impact, will not be discussed here.

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1 Primary losses

The extent of primary loss due to *P. solanacearum* depends upon the growth stage at which individual potato plants are infected, the initial inoculum load, the rate of disease development within the plant and the rate of spread from diseased to healthy plants. The extent of loss is not constant over all situations since it is influenced by the cultivar grown, the strains of bacteria present, the dispersal of inoculum throughout the field and environmental conditions (e.g. temperature, water status, soil type, etc.). If bacterial wilt leads to plant death before tuberisation then all potential yield from that plant is lost, although neighbouring plants may compensate. If wilting occurs during the tuber bulking period then yield is reduced due to lowered efficiency of the diseased plant resulting in fewer or smaller tubers, or due to brown rot of developing tubers. Other causes of primary loss are; a) development of brown rot from latently infected tubers during storage or transit; b) downgrading or elimination of seed crops under certification schemes due to excessive disease in the growing crop; c) extra costs of control measures, e.g. restricted choice of cultivars, increased price of *Pseudomonas*-free seed, roguing (labour costs and loss of yield from healthy neighbouring plants), and additional cost of grading to remove diseased tubers.

2 Secondary losses

Secondary losses occur when bacterial wilt outbreaks lead either to soil infestation or to latent infection of seed stocks; both phenomena affect production of future crops. Any loss which reduces the farmers' income may have secondary effects since capital for expenditure on future production is reduced. Soil infestation may affect production over several years through increased disease in subsequent potato or other susceptible crops. Furthermore, soil infestation may restrict farmers to grow only certain potato cultivars or alternative crops, creating market gluts, or it may force them to grow less profitable non-host crops.

3 Transitional losses

Losses of temporary nature which occur when growers change from one farming system to another are known as transitional losses (Zadoks and Schein, 1979). Such terminology is perhaps appropriate for losses due to bacterial wilt in potatoes recently introduced into the warm tropics, especially in the case of resistant varieties which become susceptible under warm growing conditions (French and de Lindo, 1982).

4 General considerations for assessment of disease intensity and yield

The methodology to assess the amount of bacterial wilt and brown rot in potato crops has been developed by French (1982) to screen genotypes for their resistance to the diseases in the field. Three factors must be considered: (a) the amount of wilting in the crop at regular intervals during the growing season, (b) the amount of tuber infection (including tubers with both visible symptoms and latent infection), and (c) the yield of marketable tubers.

Bacterial wilt

To estimate the time of disease initiation, the rate of disease development and the total incidence of bacterial wilt during a particular growing season, at least three visits to the crop are required. Weekly records are preferable but may be impractical if large areas or several sites are to be monitored. To compare data from areas with different lengths of growing season, the stage of crop development should be noted at the time of assessment; the number of days after planting may be used as a reference but should be correlated with specific growth stages, as devised by Sparks (1972). Disease intensity may be expressed as the percentage of plants wilting at each evaluation date. If large areas are to be evaluated, several rows of fixed length or plots of fixed area, chosen at random, may be evaluated per field. If wilt symptoms are not severe it may be useful to include estimates of disease severity by rating randomly sampled plants according to the scale of Martin and French

Table 1 Scale of bacterial wilt severity (after Martin and French, 1985)

State of plant	Score
Plant healthy	1
One leaf wilting	2
One-third of plant wilting	3
Two-thirds of plant wilting	4
Whole plant wilting or dead	5

(1985) as shown in Table 1.

Since bacterial wilt symptoms may be easily confused with other wilt diseases in the field, wilted plants should be sampled to determine the accuracy of the estimated disease intensity. Simple field tests, such as the oozing of milky bacterial exudate from cut stem segments suspended in clear water (Kelman, 1981), or serological testing of expressed sap from a cut stem (Digat and Cambra, 1976) may be used to verify diagnoses based on symptomatology. *P. solanacearum* strains may also be rapidly identified to race level by their reaction with specific antisera. Detailed information on other factors, biotic or abiotic, which contribute to crop loss should be collected in order to establish a crop loss profile and estimate the proportion of losses due to bacterial wilt alone. The presence or absence of nematodes (especially *Meloidogyne* spp.) is particularly noteworthy since significant increases in bacterial wilt are observed in the presence of this pest (Jatala *et al.*, 1975). Careful use of specific herbicides, nematicides, insecticides and fungicides, together with optimum agronomic management, would minimize losses due to other factors. Additional information, which should be collected is (a) cultivar of potato, (b) planting density, (c) meteorological data, and (d) identity of *P. solanacearum* strains present. Such factors influence disease intensity and can be later used to explain differences between sites.

1 Tuber infection

At harvest, the percentage of tubers with visible symptoms may be determined by examining the yield from rows of fixed length, plots of fixed area or individual plants, randomly chosen throughout the crop. Evaluating the proportion of diseased and healthy tubers by number rather than by weight may be more accurate since rotting tubers often lose weight as moisture.

Latent infection can be determined amongst the healthy appearing portion of the tuber samples either by (a) incubating the tubers at 30°C or 2-3 weeks and counting those in which disease symptoms develop or (b) dissecting and macerating portions of the vascular system of each tuber close to the stolon and determining the presence of *P. solanacearum* by serological methods (Digat and Cambra, 1976) or by plating on differential isolation medium (Kelman, 1954).

If tubers are stored after harvest, additional evaluations will be needed to assess further losses due to tuber brown rot. Replicated tuber samples, buried in net bags in bulk stores or placed in wooden trays in seed stores, may be periodically observed during the storage period and the proportion of rotting tubers noted.

2 Marketable yield

The marketable portion of the yield may be determined at harvest time, according to local grading standards, after subtracting the proportion of diseased tubers. Since marketing standards vary greatly from place to place, effects of bacterial wilt on tuber size and deformity will affect marketable yield differently in different areas. Local information on market prices should be determined wherever losses are estimated so that loss data may be expressed in cash terms. The proportion of latently infected tubers can be used to estimate additional losses during storage or in future crops if tubers are to be planted. Information regarding previous yields in the same field is useful if bacterial wilt has recently been introduced since yields before and after introduction of the disease can be compared.

Loss assessment

General methodology for crop loss assessment has been thoroughly described previously (Chiarappa, 1971 and 1981; Zadoks and Schein, 1979). Various methods may be adapted to estimate losses due to bacterial wilt as follows:

1 Statement of authority

In order to justify detailed research to quantify losses caused by a particular disease, statements of authority by experts with experience of the effects of the disease on yield are extremely useful. Hence, Kelman (1953) stated that annual losses due to bacterial wilt worldwide could only be expressed in terms of hundreds of millions of dollars. More recently, representatives from all the major potato associations rated bacterial wilt with late blight and virus diseases PLRV and PVY as the most important diseases affecting world potato production (Pavek, 1987).

2 Enquiries

Enquiries, in the form of questionnaires sent to knowledgeable people, can be a popular and relatively inexpensive way to determine crop losses. To determine the relative importance of losses caused by different potato diseases, a questionnaire was sent to regional representatives of the International Potato Center situated in different areas of the world (V. Otazu, unpublished). In 9 of the 13 countries from which a response was received bacterial wilt was amongst the three most important diseases in warm growing areas, whereas, the proportion in cool growing areas was only 3 out of 8 countries (Table 2). Presently, a more extensive questionnaire to determine major production constraints for potato production in developing countries is being sent from CIP to heads of national potato programs in all countries of regions where CIP is working. All possible limiting factors, including bacterial wilt, will be rated on a 0-3 scale of importance. On-farm enquiries can provide

Table 2 The three most important bacterial and fungal diseases causing losses in various countries as determined by postal enquiry (V. Otazu, unpublished)

Country	Warm areas			Cool areas		
Argentina	LB	BL	R			
Bolivia	LB	BL		W	PS	FB
Brazil	BW	EB	LB	LB	EB	BW
Colombia				LB	VW	FB
Chile	R	BW	LB			
Peru	LB	EB	VW	PS	FB	W
Uruguay	EB	BW	BL			
Cuba	EB	LB	BL			
Honduras	LB	BW	R			
Mexico	LB	BW	EB			
Burundi	BW	BL		LB	BW	BL
Bhutan	BW	R	EB	LB	W	EB
India	EB	BW	BL	FB	BL	R
Philippines	BW	EB	BL	BW	LB	EB

LB = Late blight, EB = Early blight, R + Rhizoctoniasis
VW = Verticillium wilt, FB = Foliar blights, PS = Powdery scab
W = Wart, BL = Blackleg + soft rot
BW = Bacterial wilt + brown rot

valuable information based on observations and growers' experience covering both direct and indirect losses. A good example is a 35-question assessment of potato production in Bukidnon, Mindanao (Kloos and Fernandez, 1985). Interviews were conducted with 262 farmers from 10 villages over a three month period, covering an estimated 110 ha of potato. Results showed that 88% of farms had bacterial wilt infestation and 49% had brown rot in storage. Most seed stocks had latent infection since no certified or imported seed was available. Additional information on average yields, choice of cultivar and cultural practices was also obtained.

3 Field experiments

Accurate information on yield losses due to bacterial wilt may be obtained from specifically designed field experiments, although the information obtained from a single experiment will be site-and season-specific. Repetition of field experiments in several locations, over at least three seasons, is necessary for loss assessment on a regional basis. All commercially important cultivars should be used. Plot sizes should be those used for yield trials, i.e. four experimental rows of 9 m length, with inter-plant and inter-row distances of 30 cm and 91 cm, respectively. These distances affect the rate of spread of bacterial wilt from plant to plant and should be standardized over all experiments. A randomized block design with at least 5 blocks is usually needed to minimize variation due to uneven soil characteristics or inoculum potential.

Fungal diseases may often be controlled with specific fungicides; losses may therefore be estimated by comparing yields from treated and untreated plots. In the case of bacterial wilt, simple chemical control is not available and broad-based soil fumigants, which tend to delay wilting (Enfinger *et al.*, 1979), also affect many other components of the crop loss profile (e.g. weeds, nematodes, soil-borne insects and other soil-borne diseases). More accurate estimates of loss caused by bacterial wilt alone may be obtained by comparing yields from plots which have been inoculated with *P. solanacearum* with those from uninoculated control plots. The simplest experiment of this type would involve soil inoculation prior to planting of healthy seed tubers and paired treatment analysis of disease intensities and yields in inoculated and uninoculated plots. Several cultivars, differing in relative resistance to bacterial wilt, could be compared.

Soil is best naturally infested by growing a diseased crop in it. This can be accomplished by planting potato tubers harvested from a wilt-infested crop, or by inoculating a susceptible crop by cutting three leaf tips per plant with scissors previously dipped in a milky suspension of *P. solanacearum* (French, 1982). The suspension may be prepared by washing cultures from agar media (Kelman, 1954) or by allowing diseased tubers or stems to ooze bacterial exudate into water. Locally isolated strains of the bacteria should be used. The diseased crop should be removed, and the new experiment planted, one month after the initiation of wilting. To inhibit movement of inoculum from inoculated to uninoculated pots, guard-rows of resistant cultivars or non-host plants could be used. Alternatively, a space of at least two rows could be left unplanted between plots. Drainage canals surrounding plots also reduce movement of inoculum in soil water from one plot to another. So that yields in the non-inoculated plots approach the maximum attainable, specific pesticides should be used and fertilizer applications and cultural practices should be optimized. Since inoculation of non-infested soil is usually highly undesirable, it may be necessary to choose a site with low inoculum potential and compare results from plots with low and high inoculum levels, although in this case information on attainable yield will not be obtained for comparisons.

More complicated multiple treatment experiments may be designed to determine factors affecting yield loss. For example, disease intensity and yields could be compared to study the effects of nematode infestation, interplant spacing or roguing on losses due to bacterial wilt. Furthermore, the effect of time of disease initiation could be studied by inoculating test plants, by the scissor method, at different times during the season. The effect of inoculum dispersal could also be studied by inoculating different numbers of test plants per plot. Results from field experiments should be expressed as regression functions and an average regression line should be calculated over several seasons and sites for a given area. Such results could then be used to model the relationship between disease intensity and yield for specific growth stages. Once a model of this kind becomes available, losses in a specific region may be estimated from disease intensity data collected from certain selected sites only.

4 Literature review

Valuable information may be extracted from the results of experiments which were not specifically designed to assess yield losses. Hence, Weingartner and Shumaker (1984) showed that due to bacterial wilt in Northeast Florida, the yield of the susceptible cv. Atlantic was only 59% that of the more tolerant cv. Sebago, although in the absence of the disease it normally gave a higher yield. Yield losses may easily be calculated from results of experiments designed to screen potatoes for resistance to bacterial wilt. Such experiments are always conducted so as to minimize losses due to other causes. Furthermore, disease intensity is usually given for different times during the growing season as well as at harvest. Much information of this type may be collected from many regions of the world where clonal screening for bacterial wilt is currently being practiced. Yield loss data may be extracted by comparing the yields of clones which demonstrate different disease intensities under the same growing conditions. Genotypic variation in yield could be minimized by studying the mean yields for several different clones which demonstrate similar disease intensities.

Jaworski *et al.* (1980) evaluated 51 potato cultivars in Georgia in 1978 and 1979. Analysis of their results reveals a significant linear correlation between disease incidence and yield loss (Fig. 1). The same relationship may also be observed by studying the results of field screening of advanced clones from the International Potato Center in Mindanao, Philippines in 1987 (Fig. 2). Interestingly, multiple regression analysis showed that the slopes of each regression line were not significantly different, suggesting similar yield loss per unit increase of disease intensity even though the experiments were conducted in different years and areas of the world (Fig. 3). A linear relationship was also observed between bacterial wilt and brown rot incidence (Fig. 4). Information of this type could be used to develop regression models to study the effect of bacterial wilt intensity on yield loss.

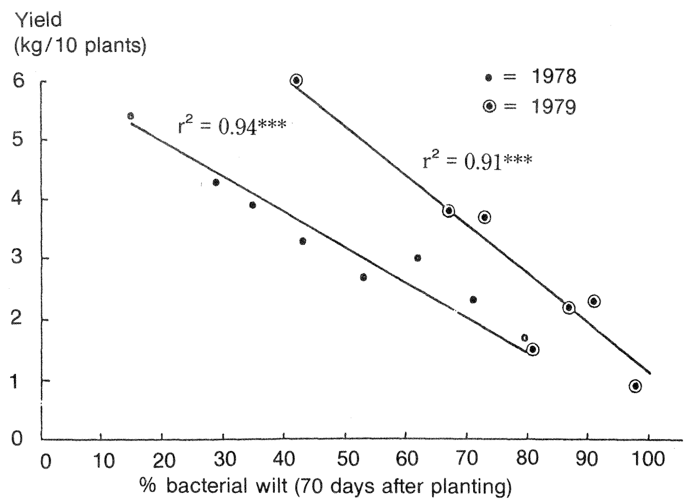

Fig. 1 Bacterial wilt incidence and yield of various potato cultivars after planting in inoculated soil in Georgia (from Jaworski *et al.*, 1980).

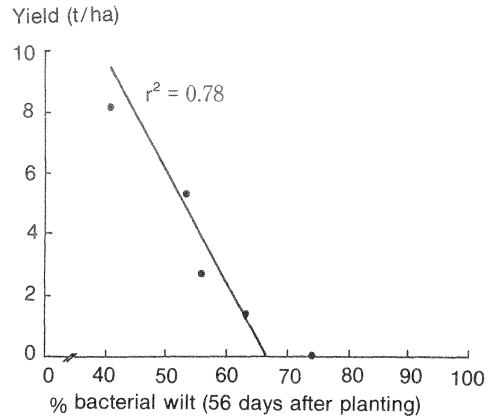

Fig. 2 Bacterial wilt incidence and yield of various potato clones after planting in infested soil in Mindanao (B. Fernandez, personal communication).

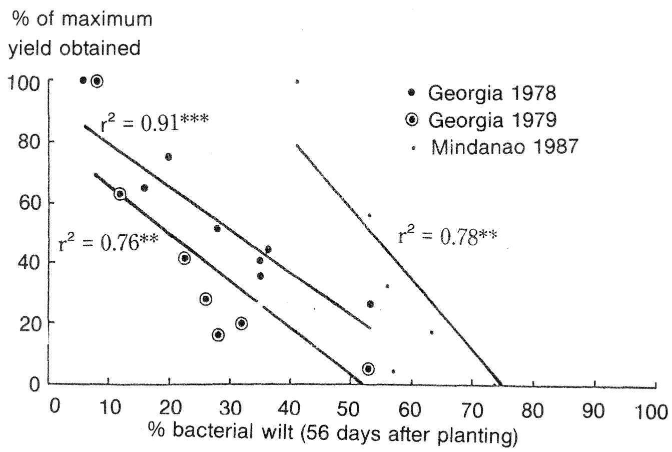

Fig. 3 Bacterial wilt incidence and its effect on obtainable yield for various cultivars and clones planted in infested soil in Georgia (Jaworski *et al.*, 1980) and Mindanao (B. Fernandez, personal communication).

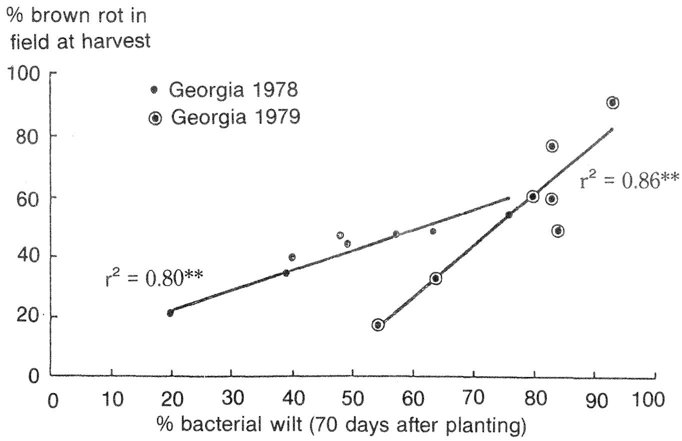

Fig. 4 Relationship between bacterial wilt and brown rot intensities on various clones planted in infested soil in Georgia (Jaworski *et al.*, 1980).

5 Surveys

Loss assessment on a regional basis is best conducted by surveys. Usually disease intensity is measured in potato fields randomly selected to represent the whole area. Quantification of all diseases present, as well as collection of complimentary data and observations, enables formulation of the crop loss profile. For each field surveyed, the cultivar grown, growth stage of the crop, presence and intensity of other factors contributing to crop loss (e.g. weeds, insects, abiotic stresses) and cultural practices should be noted. Elevation above sea level and meteorological data should be obtained where possible. If the seed origin is known the probability of it having been latently infected may often be determined.

Ideally, surveys should be repeated both within seasons and over several years since single evaluations represent only one part of a complex and dynamic system. To accurately assess crop loss, further visits to the field after harvest are required to determine yields and post-harvest losses. Subjective estimates of crop loss due to bacterial wilt based on surveys of disease intensity are shown in Table 3.

A useful example is the survey of bacterial and fungal diseases in Burundi, Rwanda and Zaire conducted by Turkensteen (1984). Two surveys were made in separate seasons over 7 major potato producing areas in the three countries. Bacterial wilt and brown rot were identified on the basis of symptomatology and serological testing with sampling and laboratory checking. The main factor contributing to yield loss was observed to be nutritional disorders. Subjective estimates of yield loss due to bacterial and fungal diseases were given as 40% of the potential yield, one-quarter of which (or 1.3 t/ha) was due to bacterial wilt and brown rot. Estimates of the crop loss profile based on field observations, growers' experience and the potential yield corresponding to average temperature and solar irradiation data are shown in Table 4.

Table 3 Importance of yield loss due to bacterial wilt and brown rot at national level as estimated from the results of surveys of disease intensify

Country	Altitude surveyed (masl)	Importance of bacterial wilt and brown rot	Estimated yield loss (%)
Burundi	1500-1800	Very important	> 30
Rwanda	1500-1800	Important - very important	10 - 30
Zaire	1500-1800	Very important	> 30
Colombia		Locally important	10 - 30
Pakistan	1600-2200	Very important	> 30
Nepal	900-2400	Important	5 - 40
Bhutan	> 2000	Locally very important	> 30
Yemen	200-1500	Not important	Negligible

1 Turkensteen (1984)
2 Turkensteen and Nieto (1984)
3 Turkensteen (1985)
4 Shrestha (1978)
5 Shrestha *et al.* (1986)
6 Kamal and Agbari (1980)

Table 4 Components of the crop loss profile for potato in Burundi, Rwanda and Zaire, as estimated by Turkensteen (1984)

Component	Yield reduction (%)	Hypothetical yield (t/ha) 2000 masl	Hypothetical yield (t/ha) 1500 masl
Potential yield*	0	73	45
Obtainable yield	10	66	41
Poor agronomic conditions	50	33	20
Virus diseases	20	26	16
Insect pests	20	21	13
Fungal/bacterial diseases	40	13	7

* Based on mean temperature and light intensity.

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Discussion

Whittle, A.M. (FAO,Indonesia): Regarding the use of the non-incremental scale of severity, how valuable is this scale in surveying for disease loss?

Answer: This scale has limited use for determining yield loss since the progression of the disease is often very rapid, especially if the potato is growing under warm temperature conditions. However, if wilt sysmptoms are not severe, and do not lead to rapid plant death, it may be useful to differentiate between different disease severities and the yield loss they cause.

Garcia, R.P. (The Philippines): According to your presentation only Bukidnon and Mindanao areas were included in your bacterial blight survey in the Philippines. I wonder why Baguio which is one of the major potato growing areas was not included in your survey. In this area, the main problem is the infestation with nematodes (*Meloidogyne incognita*).

Answer: The interaction between *Meloidogyne incognita* and bacterial wilt is well documented.