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Fungicide application and host-resistance for potato late blight management: benefits assessment from on-farm studies in S.W. Uganda

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Abstract

Late blight caused by *Phytophthora infestans*, is one of the most significant constraints to potato production in Uganda and other regions of the world. Fungicides and host plant resistance are among the most efficient control options available to growers. Field trials were conducted in 1999 and 2000 in South-western Uganda to evaluate the cost effectiveness of fungicide application regimes on six potato varieties. A factorial experiment with five fungicide application intervals (weekly, fortnightly, IPM, no spray and farmers' practice) and six potato varieties was established. Late blight infection was prevalent in both years, and a significant amount of disease was detected ($P<0.05$). Application of fungicide treatments considerably reduced late blight progress, with a corresponding increase in tuber yield. Based on monitoring of late blight disease occurrence and weather variables, two applications of the contact fungicide mancozeb on a moderately resistant variety was the most economical. Marginal rates of return and net benefits were significantly affected by fungicide applications. In the IPM treatment, late blight disease monitoring or scouting prior to first fungicide applications resulted in significant economic gains compared to scheduled applications of weekly and biweekly or no application (control) treatments.

Keywords: Mancozeb Dithane M45; Fungicide application; Host resistance; IPM; Late blight; Economic returns; Uganda

1. Introduction

Potato (*Solunum tuberosum L.*) is an important food and cash crop in South-western Uganda (Adipala, 1999). The crop has the potential to increase agricultural production in these areas (FAO, 1995) however, the damage attributed to late blight (*Phytophthora infestans* [Mont.] de Bary) has been significant and occasionally resulted in total potato crop failure in some parts of Uganda. On average yield losses due to late blight range from 40% to 60% (Olanya et al., 2002b), but losses up to 100% have been reported in other studies (Adipala, 1999). The economics and social implications of crop loss in other pathosystems have been previously described (James, 1980). Farmers in the developing countries of Africa experience serious economic losses due to the favorable environmental conditions for disease development and continuous presence of late blight inoculum (Olanya et al., 2002b). Due to high late

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blight pressure in the highland tropics, some farmers apply fungicides more than ten times per growing season (Namanda et al., 2001). In Sub-Saharan Africa, potato is one of the crops with the greatest number and amount of chemical applications. In Uganda, importation and use of pesticides has steadily increased to greater than 1000 Metric tons per year The development of resistant cultivars adapted to the tropical highlands of Africa from potato breeding programs has facilitated potato disease management by potato growers through reduction of rates of fungicide application (Hakiza, 1999). Host resistance to late blight is of significance in integrated late blight management due to its long-term economic benefits for small-scale farmers. It also minimizes changes in the population structure of *P. infestans*, decreasing the likelihood of fungicide resistance (Hakiza, 1999; Mukalazi et al., 2001).

The Ugandan National Potato Program has released potato genotypes such as Nakpot3 (CIP 575049) and Rutuku (CIP 720097) which are resistant to potato late blight. Previous reports of late blight management has documented that the use of a combination of relatively simple forecasting systems such as rainfall measurement, reduced fungicide application and host-resistance, can result in effective disease control in the Mexican potato growing valley of Toluca (Niklaus, 2000). In some parts of the tropical highlands of Africa, a combination of strategies such as host resistance, cultural practices, selection and timely application of fungicide can be effective in suppressing disease development (Olanya et al., 2001). In the low input potato farming systems of tropical Africa, there is inadequate documentation of economic benefit derived from the combination of host resistance and fungicide inputs. Therefore, the objective of this study was to evaluate yield benefits derived from utilization of host-resistance and minimum fungicide application in the highlands of Uganda.

2. Materials and methods

2.1. Field plot establishment, potato varieties and fungicide applications

Field experiments were conducted at Kalengyere Research station and at four on-farm sites in south-western Uganda during the 1999 and 2000 cropping seasons. Six potato varieties consisting of Rutuku (CIP 720097), Kabale (CIP 374080.5), Victoria (CIP 381381.20), Nakpot3 (CIP 575049), 387121.4 and 388575.5 were used. The experiment was established as a factorial (6 varieties $\times$ 5 fungicides) arranged in a randomized complete block design and replicated three times. The potato genotypes were grown in four row plots, 3 m long with spacing of 70 cm between rows and 30 cm within rows. The experimental plots were surrounded by guard rows consisting of 1 m width of wheat crop. This minimized inoculum spread between plots. The treatments were subjected to several fungicide applications. The fungicide treatments were: weekly (7 day) and biweekly (14 day) intervals, IPM, farmers' practice and control. The IPM treatment refers to scouting and monitoring of field plots for late blight symptoms prior to first application of fungicide. Subsequent applications in the IPM treatment were based on weather conditions of temperature, rainfall and relative humidity determined as favorable for late blight development. The farmers' practice was based on fungicide application beginning at 30 days after crop emergence, however, the intervals between successive sprays was not consistent and was based on their interpretation of the prevailing environmental and disease situations in the field. Therefore, a total of six applications were made under farmer's practices. In the control treatment, no fungicide applications were used. In all applications, the contact fungicide mancozeb (Dithane M45–80% WP) was used.

2.2. Disease assessment

Beginning at 30 days after planting, assessment for late blight severity was conducted at weekly intervals using a visual disease assessment scale. At plant maturity, plants were harvested and tuber yield, number of tubers as well as incidence of tuber blight per plant and plot were determined. Similarly, to evaluate treatment costs, benefits, and economic analysis, data on costs of fungicide applications (fungicide costs, labor for fungicide applications, spraying regimes, costs associated with sprayer equipment hire; harvesting and marketing costs for tubers) were recorded for susceptible and resistant varieties.

2.3. Data analyses

Data on late blight severity was used to compute area under disease progress curves (AUDPC), a measure of variety susceptibility or resistance. The AUDPC values (% disease days) were subjected to analysis of variance (ANOVA) in order to determine effects of variety resistance and fungicide applications on disease progress. To compare IPM and farmer's practice to other disease management options, means of late blight severity data, tuber yield (t/ha) and tuber blight were computed for each of the varieties for each cropping season by using Proc Means of the statistical analysis system (SAS Institute, 1985).

2.4. Economic benefits assessment

The field prices for potato tubers were calculated by subtracting the harvest and market costs from the farm gate prices that were based on 100-kg potato bags, which is a standard packing unit at farm level in Uganda. Potato tuber yield (kg/plot) was subsequently converted to tons per hectare. To determine the economic benefit of fungicide use in comparison to resistant varieties only, gross revenue of tuber yield (t/ha) was calculated, based on the local market prices and the prevailing exchange rates (Uganda Shillings 10,500 or US \$ = 7.6) for 100 kg of ware potato tubers. Since the variable costs associated with treatments such as fungicide and labor were the same for all varieties, this was calculated and used in other analysis. Marginal rate of return was calculated as gross revenue (yield in t/ha × cost per kilogram) divided by variable cost (CIMMYT, 1988). In order to assess the economic viability of late blight management practices and options, partial budget analysis, marginal rates of return, gross benefits were calculated in order to determine the net benefits or rates of return attributed to host-resistance or combination of host-resistance and fungicide application intervals (Bowen, 1997). Similarly, comparisons were also made among treatments and farmers' practice for late blight control.

3. Results

3.1. Late blight occurrence in relation to potato varieties

Late blight was recorded at all sites and cropping seasons during the period which the experiment was conducted. Late blight severity was low in 2000A, moderate in 1999 and high in 2000B cropping seasons. The application of the fungicide Dithane M45 was very effective in reducing development and progress of late blight disease on resistant varieties Nakpot 3 and Rutuku, compared to susceptible varieties Kabale and Victoria. Late blight severity (AUDPC-% diseased days) was in the range of 25.1–890, and 19.1–945 for susceptible varieties Kabale and Victoria respectively. On the resistant varieties, the AUDPC values were 13.9–510 for Rutuku and 49.7–444.5 for Nakpot3 during the 1999B cropping season (Table 1). Yield was similar between IPM and 14 day fungicide treatments (Table 2). The farmer's practice failed to decrease disease severity below that of the unsprayed (control) treatment. In general, the results of the combined analysis showed that the interaction of varieties (host resistance) and fungicides was significant at $P = 0.01$ (Table 3).

Table 1
Effect of fungicide treatments on average late blight severity (AUDPC) on potato varieties during three cropping seasons at on-farm conditions in S.W. Uganda

	Varieties[b]						
Fungicide[a] treatments	Kabale	Victoria	Rutuku	Nakpot3	387121.4	388575.5	Spray#
1999B season							
Weekly	25.1	19.1	13.9	49.7	36.1	36.3	6
Biweekly	187.8	284.4	52	99.8	175.5	162.3	3
IPM	180.9	291.8	52.2	118	229.7	109.8	2
No spray	872	913.3	510	416	715.9	884.2	0
Farmer practice	890	945.6	627.7	444.5	700	875.9	6
2000A season							
Weekly	26.5	24.7	28.1	24.2	82.4	77.2	6
Biweekly	45.6	55.2	34.2	33.7	91.2	181.9	3
IPM	90.2	61.4	45.2	36.1	91.5	153.3	2
No spray	681.9	568.2	210.4	348.5	375	505.2	0
Farmer practice	686.3	563.8	239.1	356.4	370.2	502.7	6
2000B season							
Weekly	462.2	346.4	79.7	37	90.9	180.5	6
Biweekly	862.3	395.3	86.3	23.7	171.5	268.7	3
IPM	923.4	435.2	291	285.5	216.1	395.7	2
No spray	2105	1612.6	827.1	741.4	755.2	930.4	0
Farmer practice	2073.6	1720.8	919.2	742.2	758.3	919.5	6
Means	614.19	502.19	267.74	250.45	132.8	274.34	—
LSD $_{(0.05)}$	134.54	211.54	99.68	115.7	97.8	133.4	—

[a] IPM refers to scouting and monitoring of field plots for symptoms of late blight prior to first fungicide application. Subsequent applications are based on favorable weather conditions (temperature, relative humidity and rainfall). Farmers' practice refer to first application of fungicide at 30 days after planting. Subsequent applications are based on amount of rainfall.

[b] Rutuku and Nakpot3 are resistant, 387121.4 and 388575.5 are moderately resistant clones, Kabale and Victoria are susceptible potato varieties mancozeb (Dithane M-45) was applied in all treatments except the no spray or control.

Table 2
Effect of fungicide (Dithane M-45) spray regimes on average tuber yield (Mt/ha) on six potato varieties during three cropping seasons under on-farm conditions in S.W. Uganda

	Varieties[b]						
Fungicide[a]	Kabale	Victoria	Rutuku	Nakpot3	387121.4	388575.5	Spray #
1999B season							
Weekly	40.8	41.7	34.7	36.6	45.7	44.2	6
Biweekly	36	36.2	33	35.3	35.6	40.5	3
IPM	30.8	35.8	32.6	33.8	33.6	38.3	2
No spray	6.2	7.2	13.1	12.5	8.7	11.3	0
Farmer practice	7.0	9.0	14.3	11.2	9.9	15.5	6
2000A season							
Weekly	21.7	22.7	19.5	16.4	25.2	23.9	6
Biweekly	15.6	16.9	18.8	17.1	22.5	21	3
IPM	17	13.4	17.5	18	23.3	19.2	2
No spray	4.7	3.9	10.8	12.6	9.2	11.8	0
Farmer practice	6.4	5.0	13.2	11.9	8.7	12.5	6
2000B season							
Weekly	9.6	7.5	7.6	8.3	7.3	10.9	6
Biweekly	8.1	7.0	7.0	7.2	6.7	8.8	3
IPM	6.3	6.4	6.9	7.1	6.1	8.3	2
No spray	3.6	2.6	5.4	5.9	4.0	4.4	0
Farmer practice	5.8	6.7	6.0	6.9	6.5	7.0	6
Means	14.6	14.8	16.0	16.1	16.9	18.5	—
LSD $_{(0.05)}$	3.4	4.1	4.60	3.6	3.1	3.8	—

[a] IPM refers to scouting and monitoring of field plots for symptoms of late blight prior to first fungicide application. Subsequent applications are based on favorable weather conditions (temperature, relative humidity and rainfall). Farmers' practice refer to first application of fungicide at 30 days after planting. Subsequent applications are based on amount of rainfall.

[b] Rutuku and Nakpot3 are resistant, 387121.4 and 388575.5 are moderately resistant clones, Kabale and Victoria are susceptible potato varieties mancozeb (Dithane M-45) was applied in all treatments except the no spray or control.

Table 3
Analysis of variance on the effects of fungicide treatments on late blight severity and yield on six potato varieties during 1999B, 2000A and 2000B at Kalengyere Research Station in Uganda[a]

Source	Df	MS	$P>F$
Rep	2	38218.72	0.01**
Varieties	5	88813.45	0.001**
Reps × varieties	8	34005.06	0.05*
Fungicide sprays	4	15011.51	0.001**
Varieties × fungicide Sprays	16	42068.89	0.01**
Error	32	73173.15	—

*Significant at $P<0.05$ and **significant at $P<0.01$.

[a] The fungicide Dithane M45 was applied and treatments consisted of weekly, biweekly, IPM, farmer's practice and a control (no spray). Five potato varieties with different levels of resistance were used.

3.2. *Effects of fungicide application and variety resistance on late blight control*

The weekly application of fungicide resulted in the lowest level of late blight severity recorded when compared to biweekly, IPM, farmer's practice and the control treatments. In the biweekly (14 day) application scheduling, the most effective disease management was achieved when at least three fungicide applications were made at 10, 24 and 38 days after crop emergence. In the IPM (monitor) treatment, two applications of mancozeb was effective in control of potato late blight when conditions were not favorable for late development. Based on adequate weather surveillance and scouting for disease onset, the fungicide application periods for Victoria, a susceptible variety was conducted at 10 and 31 days and for Rutuku, a resistant variety was 18 and 38 days, respectively. The late blight severity level was similar between IPM and biweekly (14 day) fungicide treatments (Table 1). The farmer's practice failed to decrease disease severity below that of the unsprayed (control) treatments.

Weekly applications of fungicide (7 day schedule) resulted in higher tuber yields in the susceptible genotypes when compared to the other treatments. Highest tuber yield was 23 (tons/ha) was recorded on the variety Kisoro. The control treatment (no sprays) had the lowest tuber yield. Potato tuber yield was higher in the resistant than the susceptible varieties. Fungicide application considerably increased the yield of susceptible varieties and also, resistant varieties, but to a lesser degree. In the IPM treatment, moderate fungicide sprays (2–3 times) increased the yield of Nakpot3 to 16 tons/ha and more than 18 tons/ha under high-frequency fungicide sprays (7 days). Susceptible cultivars such as

Table 4
Partial budget analysis (US $) for management of potato late blight on Victoria, a susceptible potato variety under different fungicide application strategies at on-farm sites in S.W. Uganda

Costs and yield	No spray	IPM(monitor)[a]	14 day	Weekly
Mean yield (t/ha)	2.6	13.4	16.9	22.7
Adjusted yield (t/ha)	2.6	12.1	15.2	20.4
Farm price /ton (US$)	56	56	56	56
Harvest cost/ton (US $)	2.8	2.8	2.8	2.8
Market cost/ton (US $)	8.3	8.3	8.3	8.3
Fungicide costs/ha (US$)	—	31	51	102
Labor costs/ha (US$)	—	34.4	56.6	113.2
Water and inputs/ha (US$)	—	17.2	28.3	56.6
Sprayer hire costs (US$)	—	31	51	102
Total variable costs/ha (US$)[b]	—	113.6	186.9	373.8
Gross field benefits/ha (US$)[c]	116.7	543.3	682.5	916
Net benefits (US$)	116.7	429.7	495.6	542.2

[a] IPM refers to scouting and monitoring of field plots for symptoms of late blight occurrence prior to first fungicide application. Subsequent applications were based on favorable weather conditions (temperature, relative humidity and rainfall).
[b] Total variable costs are costs attributed to labor and fungicide.
[c] Gross field benefits or revenue for 100 kg of ware potatoes (t/ha) based on the local market prices (Uganda Shillings 10,500 or US $ = 7.6).

Table 5
Partial budget analysis (US $) for management of potato late blight on Rutuku, a resistant potato variety under different fungicide application strategies at on-farm sites in S.W. Uganda

Costs and yield[a]	No spray	IPM(monitor)[a]	14 day	Weekly
Mean yield (t/ha)	8.3	17.5	18.8	19.5
Adjusted yield (t/ha)	8.3	15.6	16.9	17.6
Farm price /ton (US$)	61	61	61	61
Harvest cost/ton (US $)	2.8	2.8	2.8	2.8
Market cost/ton (US $)	8.3	8.3	8.3	8.3
Fungicide costs/ha (US$)	—	31	51	102
Labor costs/ha (US$)	—	34.4	56.6	113.2
Water and inputs/ha (US$)	—	17.2	28.3	56.6
Sprayer hire costs (US$)	—	31	51	102
Total variable costs/ha (US$)[b]	—	113.6	186.9	373.8
Gross field benefits/ha (US$)[c]	414.2	778.4	843.3	878.2
Net benefits (US$)	414.2	664.8	656.4	504.4

[a] IPM refers to scouting and monitoring of field plots for symptoms of late blight occurrence prior to first fungicide application. Subsequent applications were based on favorable weather conditions (temperature, relative humidity and rainfall).
[b] Total variable costs are costs attributed to labor and fungicide.
[c] Gross field benefits or revenue for 100 kg of ware potatoes (t/ha) based on the local market prices (Uganda Shillings 10,500 or US $ = 7.6).

Kabale had yield increased from less than 5 tons/ha and about 13 tons/ha when sprayed weekly and moderately with fungicide. The difference in additional yield was due to differences in host resistance.

The number of fungicide applications varied according to the scheduling period and the experimental treatments. The total number of fungicide applications was 6, 3, 2 and 0 for the weekly, biweekly, IPM (monitor) and control (non sprayed) treatments, respectively. The average fungicide costs per hectare were 31, 51 and 102 US $ for the IPM, 14 day and 7 Day application schedules. (Tables 4 and 5). In the farmers' practice the total number of fungicide applications was six. In general, average tuber yield varied according to the variety resistance and fungicide treatments. (Table 2). On the susceptible varieties Victoria and Kabale, highest tuber yield was recorded on the 7-day treatment followed by 14 day, IPM, no spray and farmer's treatments. The lowest tuber yield was recorded in the farmer's practice (Table 2). The farm gate prices varied according to the demand of a potato variety. The varieties Victoria and Nakpot3 which are used primarily for table stock were sold at an average price equivalent to US$ 56, while Rutuku, a variety with high dry matter content were sold for an equivalent to US$ 61 per ton of fresh weight basis (Table 5).

3.3. Economic benefits of late blight management practices in potato production under on-farm conditions

The results of partial budget analysis indicated that in the control treatment (no spray), gross benefit derived

Table 6
Summary of net benefits (US $) and marginal rate of returns (%) of four potato varieties with different levels of resistance to late blight and subjected to various intervals of fungicide (Dithane M45) application at on-farm sites during three cropping cycles in S.W. Uganda

Variety	Treatment[a]	TVC[b]	NB[c]	TVC change	NB change	MRR[d]
Kabale	Control	—	98.8	—	—	—
	IPM	113.6	380.3	113.6	281.5	248
Victoria	Control	—	193.1	—	—	—
	IPM	113.6	429.7	113.6	313	276
Rutuku	Control	—	414.2	—	—	—
	IPM	113.6	664.8	113.6	250.6	220
Nakpot 3	Control	—	440	—	—	—
	IPM	113.6	624	113.6	184	162

[a] IPM refers to scouting and monitoring of field plots for symptoms of late blight occurrence prior to first fungicide application. Subsequent applications were based on favorable weather conditions (temperature, relative humidity and rainfall). Farmers' practice refer to first application of fungicide at 30 days after planting. Subsequent applications are based on amount of rainfall. Control treatment refers to no fungicide application.
[b] Total variable costs (TVC) are costs attributed to labor and fungicide.
[c] Net benefits (NB) refer to total revenue minus total costs.
[d] Marginal rate of return is change in net benefits /change in total variable costs × 100%.

from planting the resistant variety, Rutuku was higher than that of the susceptible variety, Victoria. Gross benefits were higher for Rutuku compared to Victoria in the IPM, 14 day and the weekly application intervals (Table 4). Yields in the control treatment (no fungicide application) were not adjusted because there was no late blight management option applied in the control plots. Similarly, the net benefits attributed to high fungicide usage (weekly application) were higher for a susceptible variety (Table 4) compared to a resistant one (Table 5). In general, there was great net benefit from fungicide application compared to not spraying. The weekly sprays gave the highest net benefit and the net benefit derived from IPM and 14-day spraying intervals were similar. On the resistant variety, the highest net benefits were obtained in the IPM treatment. The gross benefits were similar among the IPM, 14-day and weekly treatments. (Table 5).

The results of marginal analysis showed that while the total variable costs were the same across varieties, the marginal rate of return (MRR) and change in net benefits varied among the varieties. In the susceptible varieties, the marginal rate of return in the IPM treatment was 248 and 276 for Kabale and Victoria varieties respectively (Table 6). The marginal rate of return for the IPM treatment on the resistant varieties Rutuku and Nakpot 3 were 220 and 162 respectively. These values are lower than those obtained on the susceptible varieties. The MRR was however, highest among all the treatments used in this study. Similarly, the change in net benefits attributed to use of IPM in potato late blight management were greater in the susceptible compared to the resistant varieties. The total variable costs (TVC) of fungicide application were slightly higher with farmers' practice than with weekly fungicide applications.

3.4. Relationships of environmental parameters to late blight development

Environmental conditions were conducive for late blight development during the three cropping seasons. The climatic data obtained from Kalengyere Research Station, which is representative of the sites used for on-farm trials indicated that the peak monthly rains during 1999B cropping season was recorded in October, and in 2000A cropping season, it was recorded in April. In the 2000B cropping season, maximum rainfall was recorded in October (Table 7). The average monthly relative humidity values for the three cropping cycles were 87%, 86% and 85%, respectively. Similarly, mean ambient temperatures during the cropping seasons in which potatoes were cultivated were in the range of 14.9–17°C (Table 7).

4. Discussion

Late blight occurrence was detected in all cropping seasons during the experiment. This suggests the presence of inoculum and favorable conditions for late blight development.

Previous research has indicated that the environmental conditions in the East African Highlands of Uganda and Kenya are favorable for late blight occurrence and disease development through out the year (Olanya et al., 2001).

Table 7
Summary of average rainfall, temperature and relative humidity data at Kalengyere Research Station during 1999 and 2000 cropping seasons[a]

Month	Rainfall (mm)	Min. temp (C)	Max. temp (C)	Mean temp (C)	RH (%)
1999					
January	5.5	11.2	21.5	16.4	89
February	8.4	11.6	21.5	16.6	87
March	11.4	11	20.4	15.7	86
April	8.8	11.4	20.9	16.2	84
May	4.7	11.9	21.4	16.6	86
June	0	11.4	21.3	16.3	85
July	5.6	11.4	20.9	16.1	84
August	3.7	11.3	20.7	16	82
September	7.1	11.4	20.4	15.9	83
October	11.7	11.3	19.8	15.5	83
November	8.9	11.3	19.8	15.5	83
December	11.9	11.1	19.7	15.4	86
2000					
January	5.5	11.3	21.4	16.4	85
February	6.5	11.6	22.2	16.9	86
March	6.0	10.6	20.4	15.5	86
April	4.2	10.9	20.9	15.8	85
May	3.8	11.4	21.5	15.9	87
June	0	12.3	22	16.5	86
July	0	11.8	21.5	16.6	84
August	7.7	10.9	20.2	15.5	86
September	6.8	11.4	21.3	15.8	86
October	6.3	11.1	21.1	14.9	88
November	5.7	10.5	20.2	15.5	89
Decembetr	2.6	11.4	21.2	16.3	83

[a] In 1999, the crops were planted from October 15 and harvested in January 2000 (1999 Season B). In 2000, the cropping seasons were from March 23 to July 29 (Season A), and from October 25 to January 27, 2001 (Season B).

In this study, the appearance of late blight lesions on the leaves were recorded at the period of between 12 and 15 days after crop emergence on susceptible varieties Victoria and Kabale and at 21–24 days after emergence on resistant varieties, Rutuku and Nakpot3. Our studies are in agreement with previous studies on late blight. Stevenson (1993), previously documented that under favorable conditions, late blight lesions may appear on the leaves 3–5 days after infection. Previous research has also documented that the appearance of late blight symptoms in the first 10–12 days after crop emergence often leads to severe epidemics and 80–100% foliage damage on early maturing varieties and 70–80% for medium and late varieties (Namanda et al., 2001). Other researchers have documented that mid-season or late infection may result in less severe epidemics and less yield loss (Olanya et al., 2002a). During the cropping seasons, the weather conditions (temperature, rainfall, relative humidity) at the experimental sites were not very conducive. This may explain the low severity of late blight. Severe late blight epidemics have been reported to occur in the tropics during heavy rains or moisture on potato leaves for at least 8–10 h/day h for several consecutive days (Olanya et al., 2001). Similarly, cool temperatures ($< 20°C$) and high relative humidity ($>90\%$) may be conducive for disease development. In our study, late blight severity was not very high. This may be partially attributed to a combination of the inclusion of resistant varieties in other treatments and environmental conditions, which were less than conducive, subsequent to infection.

The cost of management of late blight in low input farming systems in tropical Africa has not been adequately documented and continues to be a significant aspect of production costs. This has been attributed to a combination of high costs of inputs such as fungicides, fertilizers and seeds, weather conditions favorable for disease outbreak and development, inadequate deployment of resistant varieties and rudimentary production techniques (Sengooba and Hakiza, 1999). Management of potato late blight by using a combination of host resistance and fungicide applications in the tropical highlands of East Africa has been previously documented (Namanda et al., 2001; Kankwatsa et al., 2003).

The results of our study indicate that fungicide use alone, or host resistance alone are not adequate for control potato late blight. Although 7-day fungicide application interval resulted in the best tuber yields (tons/ha), the net returns were not sufficient to defer associated costs for the small-scale farmers. Previous research in sub-tropical environments documented that optimum management of late blight requires an integrated approach (Fry and Shtienberg, 1990). Similarly, research results have documented that in the low-input farming systems of tropical highlands of Africa, the high frequency of fungicide use and associated costs have resulted in enormous economic losses to small-scale farmers (Nyankanga et al., 2003). Therefore, the importance of using host resistance and fungicide application in controlling late blight severity as documented in this study have significant economic benefits.

The economic importance of fungicide use is attributed to the fact that the small-scale farmers in developing countries are resource constrained. Although our data suggests that application of fungicides for late blight control increased potato tuber yield, this depended on variety resistance, number and frequency of applications and weather conditions during the cropping cycles. In both resistant and susceptible varieties, our data shows that highest yield occurred when weekly spray options were used. The highest net benefit was also obtained from weekly sprays using a susceptible variety. This suggests that if susceptible potato varieties such as Victoria and Kabale is used with rigorous spray regimes, then effective late blight control and high yield can be attained. The resistant and moderately resistant potato varieties can best be used with the IPM or biweekly treatments. Similarly, based on the results of our study, the yield of resistant or moderately resistant varieties can be improved in the farmer's practice if targeted fungicide applications, based on weather parameters can be implemented. Although the number of sprays in farmer's practice was the same as weekly fungicide application, the net benefits obtained were not similar. This is due to the haphazard nature of fungicide application and irregular treatment, which involved late application of fungicides in the senescence stage of plant growth. Therefore, farmer's practice resulted into least potato tuber yield despite the numerous applications. The fungicide treatment was eliminated from the economic analysis due to the above fact. Therefore, precautions should be exercised in selecting combinations of fungicide management and host resistance that results in lowest costs and highest yield for small-scale farmers.

In our study, lower gross field benefits were obtained when nonspray treatment was applied compared to treatments in which fungicides were applied. This is indicative of the economic advantage of fungicide application in controlling potato late blight. When minimum fungicide applications were administered, higher gross benefits were obtained from the variety Rutuku compared to the variety Victoria. This may be attributed to the inherent resistance effects on disease levels. Therefore, small-scale farmers should exercise caution in fungicide use based on variety resistance to late blight. Our data reveal that more than two applications (sprays) are still economical on susceptible potato varieties but not for the resistant ones. Previous research has elucidated that variety resistance and environmental factors should play more critical role in determining fungicide application strategy (Mackenzie, 1981).

The results of the economic analyses showed that more than two fungicide applications with a contact fungicide was not economical when used on resistant varieties like Rutuku and Nakpot3. Higher net benefits from tolerant varieties (Rutuku, Nakpot 3) indicate that variety resistance is important in late blight management especially for the resource-poor farmers. In the treatment consisting of farmers' practice, the total variable cost of fungicide application was higher than the weekly application schedule. This may be explained by the fact that the farmers extended their fungicide applications to the late phases of plant growth (senescence) therefore requiring more fungicide application and coverage. In this case, the farmers' treatment or practice was considered dominant and dropped from further economic computation. In our research, a spray regime using early scouting and subsequent sprays based on weather information gave an economic benefit only when used in combination with resistant variety. This may have affected the net benefits resulting in similar net benefits between IPM and biweekly treatments. The results from previous researchers have reported the significance of fungicide use in late blight management (Hakiza, 1999). Johnson et al. (2000) reported higher variable and total costs associated with weekly or frequent fungicide applications for potato late blight management. Clayton and Shattock (1995) previously reported that use of resistant varieties resulted in a reduction in the amount of fungicide use. Our results are in agreement with the work of the above researchers.

The marginal analysis also confirmed that beyond two sprays the marginal rate of return started to decrease. The results from marginal analysis also showed that the marginal rates of return were significantly higher in the susceptible varieties compared to resistant ones. This suggests that greater yield benefits can be derived from increasing the number of applications in susceptible varieties such as Victoria and Kabale. The lower marginal rate of return suggests that it is uneconomical to implement more that two fungicide applications which does not translate into additional economic returns. In our study, the time and labor costs involved in scouting and obtaining weather data were not computed. In other studies, it was documented that farmer's choice of less risky options would protect them against risks and loss of benefits (CIMMYT, 1988). The net benefits from IPM and 14-day spray intervals were similar. This could be attributed to the similarity of environmental conditions during two cropping seasons. We anticipate that under intense rainfall conditions in a normal year, biweekly applications would not result in adequate disease control, unless a systemic fungicide such as metalaxyl is applied (Olanya et al., 2001). Therefore, the results we obtained in our research may change in seasons with intense late blight pressure.

5. Conclusions

Late blight causes substantial yield losses in various cropping seasons and in many parts of the world. Host resistance plays a key factor in late blight management, and integration of host resistance and fungicide applications enhances disease control and reduces losses, and prevents unnecessary fungicide application. Susceptible cultivars can be grown successfully when accompanied by adequate fungicide protection. Simple disease monitoring and IPM practices (two applications) reduces the need for frequent fungicide sprays and leads to high marginal rate of return (MRR).

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