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Efficacy of fungicide mixtures for the management of *Phytophthora infestans* (US-1) on potato

F.N. Muchiri[1], R.D. Narla[1], O.M. Olanya[2], R.O. Nyankanga[1], and E.S. Ariga[1]

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Fungicide application strategies (timing, frequency, rates and mixtures) are important for the control and resistance management of potato late blight caused by *Phytophthora infestans*. The efficacy of fungicide mixtures consisting of fenamidone + mancozeb and propamocarb HCL + mancozeb at various rates and in spray regimes containing metalaxyl and mancozeb was evaluated for late blight control (US-1) at four locations in Kenya. Propamocarb HCL + mancozeb significantly ($P < 0.05$) reduced foliar blight compared with mancozeb and the untreated control under moderate to severe disease pressure. Disease severity was significantly lower following application of propamocarb HCL + mancozeb at a rate of 4L ha^{-1} than at rates of 2L and 3L ha^{-1} in 1999 and 2000, but it was not significantly lower following applications at a rate of 3L ha^{-1} in 2000 and 2001. There were no significant differences in mean final late blight score among the three rates of 0.9, 1.0 and 1.1 kg ha^{-1} of fenamidone + mancozeb. All fungicide mixtures and application sequences significantly reduced the area under the disease progress curve and final late blight scores as compared with the unprotected control. Total and marketable tuber yield significantly ($P < 0.05$) increased in all fungicide-treated plots.

Keywords: Combinations, fungicide mixtures, late blight, *Phytophthora infestans, Solanum tuberosum* US-1 genotype.

[Efficacité de mélanges fongicides pour la lutte au *Phytophthora infestans* (US-1) chez la pomme de terre]

Les stratégies d'application de fongicides (calendrier, fréquence, taux et mélanges) sont importantes pour la gestion et la lutte au mildiou de la pomme de terre, une maladie causée par le *Phytophthora infestans*. L'efficacité de mélanges fongicides composés de fénamidone + mancozèbe et de propamocarbe HCL + mancozèbe à différents taux et différents régimes d'arrosage comprenant du métalaxyl et du mancozèbe a été évaluée en ce qui a trait à la lutte au mildiou (US-1) dans quatre sites au Keyna. Le mélange composé de propamocarbe HCL + mancozèbe a réduit le mildiou de façon significative ($P < 0.05$) comparativement au mancozèbe utilisé seul et au témoin lorsque la maladie était de modérée à sévère. La maladie était significativement moins sévère après l'application de 4L ha^{-1} du mélange composé de propamocarbe HCL + mancozèbe qu'après une application à des taux de 2L et 3L ha^{-1} en 1999 et 2000, mais elle n'était pas significativement moins sévère après des applications de 3L ha^{-1} en 2000 et 2001. Il n'y avait pas de différence significative dans le taux final moyen du mildiou entre les trois applications de 0,9, 1,0 et 1,1 kg ha^{-1} de fénamidone + mancozèbe. Tous les mélanges fongicides et les séquences d'application ont réduit de façon significative la surface sous la courbe de la progression de la maladie et les taux finaux de mildiou comparativement au témoin non protégé. Le rendement total et le rendement de valeur marchande des tubercules ont augmenté de façon significative ($P < 0.05$) dans toutes les parcelles traitées avec des fongicides.

Mots clés : Combinaisons, génotype US-1, mélanges fongicides, mildiou, *Phytophthora infestans, Solanum tuberosum*

1. Department of Plant Science and Crop Protection, University of Nairobi, P.O. Box 30197 - 00100, Nairobi, Kenya
2. USDA-ARS, New England Plant, Soil and Water Laboratory, Orono, ME 04469, USA; corresponding author e-mail: modesto.olanya@ars.usda.gov

INTRODUCTION

Annual costs for controlling potato (*Solanum tuberosum* L.) late blight caused by the oomycete *Phytophthora infestans* (Mont.) de Bary are estimated to be in excess of US$3.2 billion in developing countries (Anonymous 1998). In Kenya, potato production is concentrated in the densely populated highlands (1500-2500 m above sea level), and yield losses attributed to late blight range from 30 to 60% (Lung'aho *et al.* 2006; Nyankanga *et al.* 2004; Olanya *et al.* 2001). Although resistant cultivars can be effective for late blight management, inadequate cultivar deployment and ineffective fungicide application strategies can often result in huge losses and financial catastrophe (Lung'aho *et al.* 2006).

The management of late blight in Kenya remains a major production challenge because of the continuous potato cultivation that ensures abundant *P. infestans* inoculum for disease development throughout the year (Nyankanga *et al.* 2007; Olanya *et al.* 2001). Foliar blight and tuber blight have frequently been reported to occur and cause considerable losses in the tropical highlands (Nyankanga *et al.* 2007). Attempts to control late blight are almost entirely done with the use of protectant or systemic fungicides, with little regard to application strategy, in addition to other disease management options (Nyankanga *et al.* 2004, 2008; Ojiambo *et al.* 2001). A premix of Ridomil[1] (a.i. metalaxyl and mancozeb) and Dithane M-45 (a.i. mancozeb) has been widely used by potato growers for the control of late blight in the tropical highlands (Nyankanga *et al.* 2004; Ojiambo *et al.* 2001).

Published research results in other parts of the world have shown evidence of changes in the population of *P. infestans* with the emergence of more virulent and metalaxyl-resistant strains (Davidse *et al.* 1981; Dowley and O' Sullivan 1981; Fry and Goodwin 1997; Fry *et al.* 1993). In Kenya, there is no evidence for the presence of new lineages or genotypes of the pathogen, and the *P. infestans* population consists of US-1 genotype, A1 mating type (Olanya *et al.* 2001; Vega-Sanchez *et al.* 2000). However, isolates of *P. infestans* collected from potato fields in Kenya have shown a high level of metalaxyl insensitivity in areas where growers routinely and excessively use systemic fungicides for blight control in potato and tomato hosts (Hohl 1998; Ojiambo *et al.* 2001). Metalaxyl insensitivity has also been reported among some isolates in production regions with similar agroecological conditions and production techniques as those used in the Kenyan highlands (Mukalazi *et al.* 2001).

Even though fungicides are usually more effective when applied before infection occurs, this does not always happen because other factors such as rain, wind, lack of equipment and a precarious financial situation may preclude application or rapid canopy growth. In Kenya, most farmers only apply fungicides after seeing symptoms (Nyankanga *et al.* 2004). Moreover, poor protectant fungicide applications may not thoroughly cover all foliage in the canopy, resulting in lesions in parts of the canopy. Due to poor fungicide coverage, lesions at various stages of development may exist in a field before fungicides are applied. Compounds with protectant, systemic activity and post-infection efficacy may be very useful in the tropical highlands where there is continuous inoculum and control occurs mostly after infection. However, little documentation is available on the efficacy of fungicide mixtures in this region. Fungicide combinations (systemic + protectant) have been used for late blight management in other parts of the world (Platt 1983, 1985; Samoucha and Gisu 1987). Some of these fungicide mixtures include Tattoo C (31% propamocarb hydrochloride + 31% chlorothalonil), Curzate M8 (8% cymoxanil + 64% mancozeb), Acrobat MZ (9% dimethomorph + 60% mancozeb), Sereno (10 %, fenamidone + 50 % mancozeb) and Noblite (fenamidone + mancozeb) (Inglis *et al.* 1998; Mayton *et al.* 2001; Schwinn and Staub 1995). However, the efficacy of these compounds has been shown to be affected by temperature and to vary from region to region (Inglis et al. 1998; Mayton *et al.* 2001). Moreover, the higher cost of these mixtures and systemic fungicides requires some investigation into economical application rates and their fit into existing spray regimes. In southwestern Uganda, a fungicide application strategy for late blight management based on host resistance and spray scheduling has been investigated and shown to be effective (Kankwatsa *et al.* 2003).

Because of the occurrence of insensitivity to metalaxyl among isolates of *P. infestans* and post-infection application of fungicides in the tropical highlands, assessment of the efficacy of other fungicides for the management of late blight in the highland tropics is paramount. Optimization of fungicide application and assessment of fungicide efficacy may improve late blight management, minimize build-up of fungicide resistance and reduce potato production costs. Therefore, the objectives of this study were to (i) evaluate the efficacy of fenamidone + mancozeb and propamocarb HCL + mancozeb mixtures and applications rates on the development and management of late blight in comparison to mancozeb, metalaxyl and an untreated control, and (ii) determine the relationship between fungicide combination and application rates and potato tuber and marketable yield under tropical conditions. Some common anti-oomycete molecules such as cymoxanil, dimethomorph, zoxamide, triphenyltin hydroxide, cyazofamid and strobilurin compounds could not be included in this experiment due to registration requirements.

MATERIALS AND METHODS

Experimental design and layout

The experiments were conducted at four field sites in Kenya: National Potato Centre Tigoni, Mt. Kenya, Kinangop and Molo. The sites were chosen because

1. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation for endorsement by the University of Nairobi or the U.S. Department of Agriculture.

Table 1. Average temperature, relative humidity, precipitation, and number of rainy days recorded at Tigoni, Kenya, during the cropping months in 1999-2000 and 2000-2001

Year[a]	Month	Temperature (°C)	Relative humidity (%)	Precipitation (mm)	Rainy days (nb)
1999/2000	Oct	17.9	85.7	61.0	–
	Nov	16.5	89.2	398.2	20
	Dec	16.0	83.3	231.4	16
2000/2001	Oct	18.8	84.7		–
	Nov	16.7	81.8	199.0	16
	Dec	18.1	87.5	121.5	18
	Jan	19.2	85.8	451.8	–

[a] Potato plots were planted on October 20, 1999 and October 19, 2000 during the short rainy seasons, and on March 15, 2000 during the long rainy season.

of their different temperature and precipitation conditions and because differences were observed in late blight pressure among the locations (Ojiambo *et al.* 2001). The experiments were conducted in 3 m x 4.5 m (width x length) plots consisting of 5 rows planted with 16 seed tubers in a randomized block design. A standard agronomic inter-row spacing of 0.75 m and intra-row spacing of 0.3 m for this region were used for all trials. In all experiments, Kerr's Pink, a cultivar susceptible to late blight under Kenyan conditions and grown in many regions producing potato for fresh consumption, was used. Sprouted potato seeds were planted on October 20, 1999 and October 19, 2000 during the short rainy season, and on March 15, 2000 during the long rainy season. Diammonium phosphate (DAP) fertilizer was applied at a rate of 500 kg ha^{-1} and was incorporated into field plots at planting time during all cropping seasons. The plots were hilled three times during crop growth. Limited supplemental sprinkler irrigation was used where necessary and weed management was carried out by conventional tillage between rows.

Measurement of weather variables

Weather data were obtained from a weather station located at the experimental site of Tigoni during both years. Precipitation was recorded with a rain gauge, and temperature and relative humidity were recorded with minimum and maximum thermometers at Tigoni (Table 1). No climatic data was recorded from the Molo, Kinangop and Mt. Kenya locations.

Experimental treatments

Effects of fungicide mixtures and application rates on late blight development at Tigoni

Field trials were conducted at the National Potato Research Center during the 1999-2000 and 2000-2001 cropping seasons. The fungicides used in this experiment were propamocarb HCL (Tattoo, Agr-Evo Products, Inc., USA); mancozeb (Dupont Agricultural Products, Delaware, USA); fenamidone (Noblite, Rhone-Poulenc Products, France), and metalaxyl (Ridomil MZ, CIBA Products Inc., Switzerland). The treatments consisted of propamocarb HCL + mancozeb (at three application rates), fenamidone + mancozeb (at three

Table 2. Fungicide treatment compound mixtures, rates, dosage and number of applications evaluated for late blight (*Phytophthora infestans*) control on potato during the 1999-2000 and 2000-2001 cropping seasons at Tigoni, Kenya

Fungicide compound	Active ingredients[a]	Application dosage[b]	Application rate	Number of applications[c]
Noblite	Fenamidone + mancozeb	100 g kg^{-1} fenamidone/ 500 g kg^{-1} mancozeb	0.9, 1.0, 1.1 (L ha^{-1})	4
Tattoo	Propamocarb HCL + mancozeb	248 g L^{-1} propamocarb HCL/ 301.6 g L^{-1} mancozeb	2.0, 3.0, 4.0 (L ha^{-1})	4
Dithane M-45	Mancozeb	–	1.5, 2.5 (kg ha^{-1})	4
Ridomil	Metalaxyl + mancozeb	–	2.5 (kg ha^{-1})	4
Untreated (control)[d]	–	–	–	–

[a] Combinations of fungicide active ingredients used for late blight control.
[b] Dosage of the active ingredients in the mixtures.
[c] Number of applications during a cropping season.
[d] No fungicide applied, plants treated with water.

application rates), mancozeb (at two application rates), metalaxyl and an unprotected control. The experimental plots were arranged in a randomized complete block design with four replications. In all cases, late blight was initiated from natural inoculum during the cropping season. Fungicide applications were initiated at the time of appearance of late blight symptoms on potato plants in experimental plots, similarly to the application strategies used by farmers. Details on application dosage and rates are shown in Table 2. Fungicides were applied at 10-d intervals using a Neptune knapsack sprayer with a hollow cone nozzle. The sprayer was calibrated prior to the first fungicide application so as to deliver a spray volume of 400 L ha^{-1} at a pressure of 3 bars. Potato plants in the control plots were sprayed with water.

The experiment was repeated during the 2000-2001 cropping season using the same treatments and number of replications described above. Treatments and plots were randomized between years. The cultivar Kerr's Pink was used for all experiments.

Effects of fungicide mixtures, application sequences and intervals on late blight development at the Molo, Kinangop and Mt. Kenya locations

Trials using different combinations and sequences of fungicides were conducted at Molo, Kinangop and Mt. Kenya. They were compared with the application strategies used by potato growers obtained from a survey conducted in the three main potato growing regions in the highlands and with the untreated control. The experiment was designed to test the various application strategies with the cultivar Kerr's Pink at each of the above sites during the 2000-2001 cropping season in relation to farmers' practices. At all locations, late blight was initiated from natural inoculum during the cropping season. Fungicide applications were initiated at the onset of late blight symptoms. Details on the fungicide compounds, rates, intervals, number and application sequences are summarized in Table 3.

Table 3. Fungicide combinations, application sequences, rates, number of applications and application intervals used in the management of potato late blight (*Phytophthora infestans*) at the Molo, Kinangop and Mt. Kenya locations during the 2000-2001 cropping season

Location	Treatment sequence	Fungicide compound[a]	Application rate (kg ha^{-1})	Number of application[b]	Application interval[c] (d)
Molo	1	Mancozeb	2.5	2	7
		Fenamidone	1.0	1	7
		Propamocarb HCL	4.0	1	7
Molo	2	Mancozeb	2.5	2	7
		Fenamidone	4.0	1	7
		Propamocarb HCL	1.0	1	7
Molo[d]	3	Mancozeb	2.5	2	5
		Metalaxyl	2.5	2	14
Kinangop	1	Mancozeb	2.5	1	7
		Propamocarb HCL	4.0	1	7
		Fenamidone	1.0	1	7
		Propamocarb HCL	4.0	1	7
Kinangop	2	Propamocarb HCL	4.0	1	7
		Mancozeb	2.5	1	7
		Propamocarb HCL	1.0	1	7
		Propamocarb HCL	4.0	1	7
Kinangop[d]	3	Metalaxyl	2.0	4	14
Mt. Kenya	1	Mancozeb	2.5	2	7
		Fenamidone	1.0	2	7
		Propamocarb HCL	4.0	2	7
Mt. Kenya	2	Mancozeb	2.5	2	7
		Propamocarb HCL	4.0	1	7
		Fenamidone	1.0	1	7
		Propamocarb HCL	4.0	1	7
		Fenamidone	1.0	1	7
Mt. Kenya[d]	3	Mancozeb	2.5	6	7
		Metalaxyl	0.5	3	7

[a] Different fungicide sequences or treatments used at the three locations.
[b] Number of applications for each product in a sequence.
[c] Interval at which fungicides were applied.
[d] Fungicide application strategy commonly used by potato farmers.

Late blight and tuber yield assessments

At the Tigoni research site, potato late blight severity was assessed by visual rating of foliage in the three inner rows. Visual rating of percent leaf area blighted was performed using a scale of 0 to 100%, where 0% = no disease and 100% = total foliage damaged (James 1971). Disease severity assessment was initiated when the first symptoms were observed in the control plots. Subsequent evaluations of late blight severity were performed at 7-d intervals.

At the highland sites of Molo, Kinangop and Mt. Kenya, field plots were assessed when late blight severity in the control plots exceeded 5% of foliar damage at 7-d intervals.

Tubers from the three inner rows of each experimental plot were harvested. The tubers were washed and their weight was determined (Salter suspended weighing machine, Model 235). Tubers in all plots were also separated into marketable (tuber diam > 6.4 cm) and unmarketable (tuber diam < 6.4 cm). Tuber weight was converted to metric tons per hectare for subsequent analysis.

Statistical analysis

Foliar blight was analyzed by using disease severity assessment to compute the area under the disease progress curve (AUDPC) as described by Shaner and Finney (1977).

Table 4. Effect of fungicide mixtures on late blight (*Phytophthora infestans*) severity, AUDPC, and mean total and marketable tuber yield during the 1999-2000 and 2000-2001 cropping seasons at Tigoni, Kenya

Fungicide mixture[a]	Application rate (ha^{-1})	Final disease severity (%)	AUDPC[b]	Total yield ($t\ ha^{-1}$)	Marketable yield ($t\ ha^{-1}$)
1999-2000					
Untreated control	–	98.5	773.2	5.5	2.0
Fenamidone + mancozeb	0.9 L	56.3	390.3	14.7	8.3
	1.0 L	55.0	356.5	14.9	9.3
	1.1 L	53.8	334.1	16.1	8.8
	(LSD $_{(0.05)}$)[d]	2.7	48.8	1.3	1.9
Propamocarb HCL + mancozeb	2 L	40.0	242.2	18.7	11.7
	3 L	33.1	239.4	22.4	15.1
	4 L	26.8	172.8	23.6	16.4
	(LSD $_{(0.05)}$)[d]	6.1	53.8	3.5	3.3
Mancozeb	1.5 kg	66.5	437.1	14.1	8.8
	2.5 kg	63.0	438.3	16.7	9.6
	(LSD $_{(0.05)}$)[d]	3.6	12.3	2.7	0.8
Metalaxyl	2.5 kg	8.5	43.6	36.0	26
LSD $_{(0.05)}$[c]		21.5	30.2	6.3	5.5
2000-2001					
Untreated control	–	81.3	566.1	12.0	9.3
Fenamidone + mancozeb	0.9 L	13.8	66.8	16.9	13.5
	1.0 L	9.4	46.2	18.1	15.0
	1.1 L	8.8	37.5	20.1	15.1
	(LSD $_{(0.05)}$)[d]	5.7	20.6	2.2	1.2
Propamocarb HCL + mancozeb	2 L	10.6	36.9	18.3	16.7
	3 L	5.4	25.1	18.8	16.3
	4 L	4.5	24.9	20.1	17.7
	(LSD $_{(0.05)}$)[d]	5.9	12.4	1.8	1.0
Mancozeb	1.5 kg	63.5	436.1	14.9	12.3
	2.5 kg	51.4	405.9	15.7	13.8
	(LSD $_{(0.05)}$)[d]	12.4	31.0	0.8	1.5
Metalaxyl	2.5 kg	8.0	24.4	21.9	17.3
LSD $_{(0.05)}$[c]		12.5	26.2	2.9	3.8

[a] Fungicides and fungicide mixtures used in efficacy studies.
[b] AUDPC calculation based on visual disease assessments (%) over time.
[c] LSD values refer to a comparison of means for the different fungicides within one cropping season.
[d] LSD values in parentheses refer to a comparison of means for the different rates of application of one product or mixture.

The effects of fungicide mixtures and application rates on foliar blight severity, AUDPC, and total and marketable yield were computed by ANOVA using SAS Proc GLM analysis (SAS /STATS Version 9, Cary, NC). For the Tigoni experiments, the effects of fungicide mixtures and application rates were analyzed as factorial combinations. When ANOVA indicated significant differences among treatments, mean late blight severity and total and marketable tuber yield were separated by Fisher's LSD statistics. The progress of late blight severity among treatments and across assessment periods was plotted and examined graphically.

RESULTS

Weather conditions

Weather conditions during the 1999-2000 cropping season were favourable to late blight development. Total precipitation in November and December was fairly high and relative humidity was also sufficient for late blight infection (Table 1). In the second rainy season (mid-March to July in 2000), precipitation was unreliable. The crop was brought up under sprinkler irrigation, but no late blight symptoms were observed and no data were obtained. During the 2000-2001 cropping season, temperature and precipitation were sufficiently conducive to pathogen infection, though average relative humidity was somewhat lower (Table 1). No climatic data were recorded at the Molo, Kinangop and Mt. Kenya locations; however, those regions are wet and cool due to the high altitudes.

Effects of fungicide mixtures and application rates on late blight development at Tigoni

During the 1999-2000 season, the first late blight symptoms were observed 41 d after planting. Disease increased rapidly in unprotected plots with 98.5% late blight severity 35 d after initial detection of the disease. All fungicides, regardless of the application rate, had significantly lower AUDPC and final disease severity scores than the untreated control (Table 4). The propamocarb HCL + mancozeb application rate of 4 L ha^{-1} resulted in significantly lower late blight severity than application rates of 2 L ha^{-1} and 3 L ha^{-1} (Table 4). Late blight severity was significantly lower ($P \leq 0.05$) in propamocarb HCL + mancozeb treated plots compared with the ones treated with mancozeb (Tables 4 and 5). Variations in disease development and severity were observed among treatments at various assessment dates. Potato plants treated with the propamocarb HCL + mancozeb mixture showed moderate disease development, while mancozeb-treated plants exhibited higher late blight severity and metalaxyl-treated plants had the lowest level of disease severity at each assessment (Fig. 1). No significant differences in final late blight severity among potato plants treated with fenamidone + mancozeb were observed for the various application rates (Table 4). The application of metalaxyl resulted

Table 5. Orthogonal contrasts of mean final disease severity, AUDPC, and total yield of potato in field experiment conducted with fungicide mixtures during the 1999-2000 and 2000-2001 cropping seasons at Tigoni, Kenya

		1999-2000			2000-2001		
Orthogonal contrast	Parameter	MS	*F* value	*P* > *F*	MS	*F* value	*P* > *F*
Treatment vs control	Disease severity	1072.4	55.6	0.007**	2072.0	94.36	0.02*
	AUDPC	22816.73	139.04	0.0011**	3911.6	23.84	0.0144*
	Total yield	38.1	10.83	0.0217*	19.85	18.64	0.0203*
Fenamidone/mancozeb vs mancozeb	Disease severity	113.3	5.87	0.0598	1500.1	9.14	0.0529*
	AUDPC	5418.7	1.02	0.3340	6234.9	4.01	0.01**
	Total yield	70.4	8.04	0.0623	232.6798	1.42	0.3905
Fenamidone/mancozeb vs metalaxyl	Disease severity	2109.4	109.37	0.001**	1630.2	74.24	0.03*
	AUDPC	25241.9	4.76	0.0518*	41767.2	19.99	0.01**
	Total yield	18.6	11.49	0.0365*	883.57	5.38	0.1017
Propamocarb HCL/mancozeb vs metalaxyl	Disease severity	4050.00	109.99	0.01**	380.0104	19.70	0.068
	AUDPC	48547.7	92.04	0.01**	11861.9	930.93	0.01**
	Total yield	79.4	54.57	0.007**	76.9	0.38	0.5630
Propamocarb HCL/mancozeb vs mancozeb	Disease severity	1417.0	73.47	0.04**	79.2067	0.08	0.7830
	AUDPC	1724.5	32.92	0.01**	13784.5	33.53	0.01**
	Total yield	901.9	3.83	0.0142**	1101.163	6.71	0.0781
Propamocarb HCL/mancozeb vs fenamidone/mancozeb	Disease severity	759.4	39.37	0.015*	3515.4077	1.57	0.2153
	AUDPC	74995.4	86.35	0.02*	8023.1	3.93	0.0543*
	Total yield	119.7066	34.06	0.021*	24.0	16.50	0.097
Metalaxyl vs mancozeb	Disease severity	1624.1	84.2	0.003**	53.3	2.4	0.643
	AUDPC	30817.5	257.2	0.001**	2007.3	15.9	0.008**
	Total yield	221.9	88.1	0.002**	57.4	7.6	0.0399*

*,** mean significantly different at 5% and 1%, respectively.

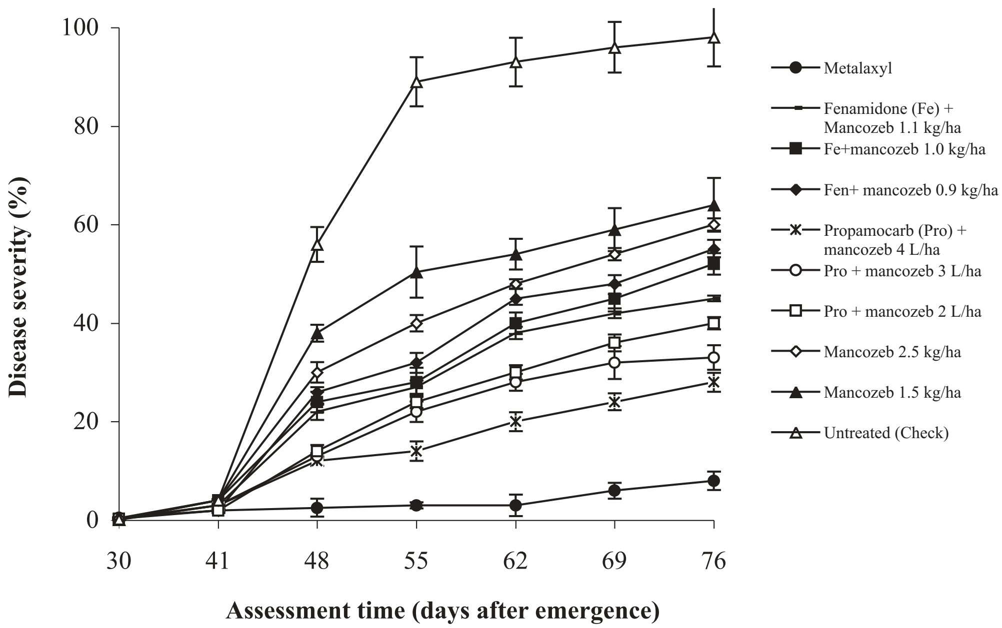

Figure 1. Progress of potato late blight (*Phytophthora infestans*) on cultivar Kerr's Pink treated with different fungicides at the Tigoni Research Station during the 1999-2000 cropping season. On each day of assessment, values = mean disease severity. The vertical bars represent standard errors of the mean.

in significantly (P < 0.05) lower late blight severity compared with all other treatments (Table 4 and Fig. 1). During the 1999-2000 growing season, the fungicide mixtures had variable suppressive effects on disease development. Orthogonal contrasts showed that fenamidone + mancozeb versus the mancozeb treatment was not significant, while propamocarb HCL + mancozeb versus the mancozeb treatment was significant (Table 5).

At Tigoni, disease severity was considerably higher during the 2000-2001 cropping season compared with the 1999-2000 season (Table 4 and Fig. 2). During the final assessment, the control and propamocarb HCL + mancozeb (4 L ha^{-1}) treated potato plants had the highest and lowest late blight levels, respectively (Table 4). Late blight severity in plants treated with propamocarb HCL + mancozeb applied at rates of 2 L ha^{-1} (10.6%) and 4 L ha^{-1} (4.5%) differed significantly (P < 0.05). Plants treated with mancozeb (1.5 kg ha^{-1} and 2.5 kg ha^{-1}) and metalaxyl (2.5 kg ha^{-1}) had a final late blight severity of 63.5, 51.4 and 8%, respectively. Development of late blight was greater in the control plants compared with plants treated with mancozeb, fenamidone + mancozeb and metalaxyl (Fig. 2). Development of late blight was also greater in the control plots compared with the ones treated with propamocarb HCL + mancozeb. Orthogonal contrasts of fungicide treatments versus unprotected control, and of mixture treatment comparisons, revealed significant differences in late blight severity, AUDPC and total yield between many treatments (Table 5).

Effect of fungicide mixtures, application sequences and intervals on late blight development at the Molo, Kinangop and Mt. Kenya locations

All fungicide treatments, regardless of the fungicide mixture, sequence and application rate, had significantly lower disease severity and AUDPC values than the untreated control (Table 6).

In Molo, fungicide mixtures and application sequences significantly reduced late blight severity compared with the untreated control (Table 6). However, no significant differences were observed in late blight severity among treatments (sequences) 1, 2 and 3 at this location. In this region, two applications of mancozeb (2.5 kg ha^{-1}) followed by one application of fenamidone + mancozeb (1 kg ha^{-1}) and a single application of propamocarb HCL + mancozeb (4 L ha^{-1}) at 7-d intervals (sequence 1) did not significantly improve late blight control compared with sequences 2 and 3.

At the Kinangop and Mt. Kenya locations, late blight levels were also significantly higher in untreated plots compared with treated ones (Table 6). In these two regions, treatments (application sequences and combinations of spray intervals) were not significantly different, except when compared with the untreated plants (Table 6).

Effect of fungicide mixtures and application rates on tuber yield at Tigoni

During the 1999-2000 season, propamocarb HCL + mancozeb and mancozeb alone, both applied at different rates, resulted in significantly higher yield (P < 0.05) than that obtained with the untreated plants (Table 4). Application of propamocarb HCL + mancozeb

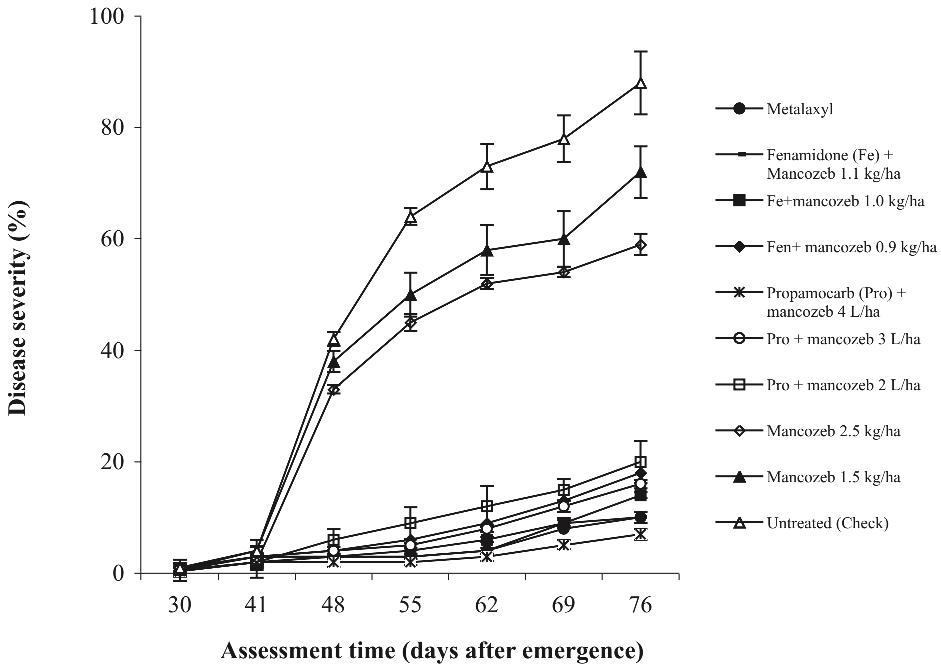

Figure 2. Progress of potato late blight (*Phytophthora infestans*) on cultivar Kerr's Pink treated with different fungicides at the Tigoni Research Station during the 2000-2001 cropping season. On each day of assessment, values = mean disease severity. The vertical bars represent standard errors of the mean.

at a rate of 4 L ha^{-1} resulted in significantly higher yields compared with application rates of 2 and 3 L ha^{-1}. Plants treated with metalaxyl had the highest total yield (36 t ha^{-1}) during the 1999-2000 season. Mancozeb treatments at 1.5 and 2.5 kg ha^{-1} resulted in total tuber yields of 14.1 and 16.7 t ha^{-1}, respectively. Marketable tuber yield also differed significantly between all fungicide treatments and the control (Table 4). Marketable yields ranged from 2 t ha^{-1} (untreated) to 26 t ha^{-1} (metalaxyl-treated plants) in 1999-2000. No significant differences in yield were observed between fenamidone + mancozeb and mancozeb alone. The metalaxyl-treated plants showed significantly higher marketable tuber yield than all other fungicide-treated plants in 1999-2000.

In 2000-2001, total yield ranged from 12 to 21.9 t ha^{-1} in the untreated control and metalaxyl-treated plants, respectively (Table 4). No difference in total yield was recorded among treatments in which three rates of propamocarb HCL + mancozeb were applied. Plants treated with metalaxyl had significantly higher total yield compared with those treated with mancozeb (Tables 4 and 5). Marketable tuber yield ranged from 9.3 t ha^{-1} in untreated control plots to 17.3 t ha^{-1} in metalaxyl-treated plots (Table 4). No significant differences in yield were observed between fenamidone + mancozeb and mancozeb alone (Table 5).

Effect of fungicide mixtures, application sequences and intervals on yield at the Molo, Kinangop and Mt. Kenya locations

The three regions showed differences in efficacy of spray programs containing propamocarb HCL + mancozeb and fenamidone + mancozeb (Table 6). In Molo, the sequence involving two applications of mancozeb (2.5 kg ha^{-1}) followed by one application of fenamidone + mancozeb (1 kg ha^{-1}) and one application of propamocarb HCL + mancozeb (4 L ha^{-1}) at 7-d intervals gave numerically better total and marketable yields, even though the results were not statistically significant. In Kinangop, there were no significant differences among the sequences while for the Mt. Kenya region, the best yields were achieved using the third sequence, i.e. mancozeb followed by metalaxyl (Table 6).

DISCUSSION

The mixtures of propamocarb HCL + mancozeb and fenamidone + mancozeb were effective in controlling late blight in established epidemics compared with the application of mancozeb alone or the untreated control. However, none of the fungicide mixtures was more effective than metalaxyl. The relatively enhanced disease control obtained with fungicide mixtures under moderate to severe late blight conditions suggests that fungicide mixtures can provide effective late blight management in established epidemics compared with the use of a protectant fungicide. Fungicide mixtures have been shown to provide effective late blight control incited by the US-1 genotype of *P. infestans* (Mayton *et al.* 2001; Platt 1985). Mixtures of systemic and protectant fungicides were equally effective for the control of late blight and downy mildew in various experiments (Samoucha and Gisu 1987). Mixtures have also been shown to be very effective when applied prior to infection (Cianchetti *et al.* 2000). The propamocarb HCL + mancozeb mixture has been shown to suppress epidemics through the suppression of disease progress and lesion expansion (Mayton *et al.* 2001).

Fenamidone, from the imidazolinone family, posses-ses preventive and anti-sporulant properties that have an impact on direct germination of sporangia (Bardsley *et al.* 2002; Mercer and Latorse 2003). In our study, the late blight control exhibited by the mixtures could be attributed to the active ingredients in the mixture which have different chemistries, and their efficacy may be attributable to their different modes of action. Perhaps this may also be due to the fact that more active ingredients were applied in the mixtures, or it may be a result of both the fungicide chemistries and quantity factors.

Metalaxyl-treated plants sustained less late blight damage compared with the plants exposed to fungi-cide mixtures. In general, metalaxyl is effective for controlling diseases incited by oomycetes because it is absorbed by the leaves and roots under various environmental conditions (Easton and Nagle 1985). This may be the case in our tropical experimental set-ting where variable climatic conditions exist, but metalaxyl is still effective on late blight incited by the US-1 genotype. The relatively higher late blight dis-ease severity recorded in mancozeb-treated plants at 1.5 and 2.5 kg ha^{-1} suggests that protectant fungicide treatments initiated after the appearance of late blight symptoms or after disease establishment may not be effective for disease control. This is in contrast to other late blight research reports, which showed that mancozeb applied as a protectant can be effective in reducing the impact of late blight under tropical conditions (Namanda *et al.* 2004). It is possible that application timing and intervals between applications for mancozeb may not have been sufficient to optimize its effectiveness in this experiment. Therefore, contact or protectant fungicides need to be used preventatively instead of post-infection for effective control of late blight (Johnson *et al.* 2000; Mayton *et al.* 2001).

Differences in late blight severity were observed between the 1999-2000 and 2000-2001 cropping seasons; however, the use of mixtures was effective for disease control in both seasons. The differences in disease levels may be attributed to the dry weather conditions that were experienced immediately following the appearance of late blight symptoms (41 d after planting) during the 2000-2001 season or to fungicide efficacy. Variation in late blight incidence and severity has been reported previously for various locations in Kenya (Nyankanga *et al.* 2004; Olanya *et al.* 2006). The variation in disease development among the different treatments may have been due to the different chemistries of the fungicides used. Fenamidone possesses the special property of “apical diffusion”, which protects young developing organs from a treated bud (Bardsley *et al.* 2002; Gisu 2002; Mercer and Latorse 2003; Rhone 2003). As the newly formed plant tissues grow, the product is distributed and protects the young shoots. This property of fenamidone helps to protect the upper part of the potato plant.

Table 6. Effect of different fungicide mixture treatments and application sequences on potato late blight (*Phytophthora infestans*) severity and tuber yield at three locations in the Kenya highlands during the 2000-2001 cropping season

Location	Treatment sequence	Total number of fungicide applications	Late blight severity: Foliage severity (%)	Late blight severity: AUDPC	Tuber yield: Total (t ha^{-1})	Tuber yield: Marketable (t ha^{-1})
Molo[a]	1	4	5.1	43.1	15.6	14.3
	2	4	5.6	39.6	14.3	13.2
	3[d]	4	6.3	44.3	13.1	11.4
	Untreated	0	85	345	6.3	5.1
	LSD (0.05)		6.1	24.6	6.6	7.0
Kinangop[b]	1	4	8.5	50.5	13.0	9.1
	2	4	7.0	47	12.5	10.8
	3[d]	4	18.0	98.6	13.7	9.3
	Untreated	0	89	574.8	5.6	5.3
	LSD (0.05)		8.5	32.3	5.1	3.8
Mt. Kenya[c]	1	6	11.3	65.3	11.0	8.8
	2	6	7.5	44.0	11.6	9.9
	3[d]	9	4.0	30	12.8	11.7
	Untreated	0	91	622.8	5.1	5.6
	LSD (0.05)		6.2	34.1	4.7	3.9

[a] Molo: sequences 1 and 2 = mancozeb (applied twice) and fenamidone + mancozeb and propamocarb HCL + mancozeb (applied once); sequence 3 = two applications of mancozeb and two applications of metalaxyl. See Table 3 for application rates.

[b] Kinangop: sequence 1 = mancozeb, propamocarb HCl + mancozeb, fenamidone + mancozeb, propamocarb HCL + mancozeb, applied in that order; sequence 2 = propamocarb HCL + mancozeb, mancozeb, propamocarb HCL + mancozeb (twice), applied in that order; sequence 3 = metalaxyl applied four times during a season. See Table 3 for application rates.

[c] Mt. Kenya: sequence 1 = mancozeb, fenamidone + mancozeb, propamocarb HCL + mancozeb, each applied twice in that order; sequence 2 = mancozeb (twice) and propamocarb HCL + mancozeb, fenamidone + mancozeb, propamocarb HCL + mancozeb, fenamidone + mancozeb, in that order; sequence 3 = six and three applications of mancozeb and metalaxyl, respectively. See Table 3 for application rates.

[d] Fungicide application strategy commonly used by potato farmers.

Different regions showed differences in effectiveness of spray programs containing propamocarb HCL + mancozeb and fenamidone + mancozeb. However, alternation of fungicide mixtures with either metalaxyl or mancozeb did not improve the efficacy of either foliar blight control or yield. This is contrary to what we expected, especially the alternation of fenamidone + mancozeb and propamocarb HCL + mancozeb, which we anticipated to have better control. In other late blight studies, fungicide application schemes that included cymoxanil, dimethomorph, or propamocarb hydrochloride provided slightly better control of late blight in a North American fungicide trial than schemes that did not include those fungicides (Inglis *et al.* 1998).

High tuber yield was obtained with plants treated with fungicide mixtures and metalaxyl during both years. This suggests that compound mixtures are effective for blight control and can result in improved tuber yield under humid tropical conditions. This also implies that mixtures of fenamidone + mancozeb and propamocarb HCL + mancozeb can be used as substitutes for metalaxyl in late blight control incited by the US-1 genotype under wet and humid tropical conditions, or when foliar blight is moderate. Higher tuber yields resulting from the use of different fungicide compounds, application rates and strategies have previously been reported in the highland tropics (Kankwatsa *et al.* 2003; Ojiambo *et al.* 2001). It should be noted that under our experimental setting, it was difficult to determine whether the effect of mixtures was synergistic or additive due to the fact that propamocarb HCL and fenamidone were not applied alone as treatments. At low to moderate disease levels, there were no differences between the rates; the lower rate could therefore be used. However, rate effects resulted in significant differences in disease levels. We were unable to analyze the costs and benefits associated with fungicide mixtures in this study. This is a drawback because costs related to fungicides, application rates as well as other variables, which would enable us to compute yield revenues, were not compiled.

We conclude that fungicide mixtures can be beneficial to late blight management in established epidemics. Apart from their effective disease control, half-rates of fungicides are applied in the mixtures, which reduces the actual amount of recommended fungicide rates, the costs as well as environmental degradation. Another significant attribute is the possible indirect effect of the mixtures on minimizing selection pressure in pathogens as a result of the multi-site action of mixture compounds. Even though the economic benefit of mixtures was not precisely quantified in this experiment, it is presumed that the use of mixtures can result in better late blight control and acceptable tuber yield, as demonstrated by our results.

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