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Study on Biological and Economic Considerations in the Control of Potato Late Blight and Potato Tuber Blight

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Abstract

An economic analysis was made of old results from 1993-1996 (22 field trials) and new results from 2010-2013 (12 field trials) obtained in field trials with different doses of fungicides to control potato late blight (PLB) and potato tuber blight (PTB) caused by *Phytophthora infestans*. The objective was to determine the economically optimal dose for effective control.

In 1993-1996, the economic net return was highest for long intervals of about two weeks between treatments and a dose of 60% of the recommended level. The difference between the experimental treatment with the highest net return and the untreated control was 1587 € per hectare (ha^{-1}) in susceptible cultivars, but only 531 € ha^{-1} in moderately resistant cultivars. In addition, the mean difference in net return between all treated susceptible and all treated moderately resistant cultivars was 874 € ha^{-1}. In the half of the field trials with the lowest maximum attack of PLB, the difference between the experimental treatment with the highest economic income and untreated control was 547 € ha^{-1}, while it was 1571 € ha^{-1} in the half of the trials with the highest maximum attack.

The results for 2010-2013, which were all based on a short treatment interval of about one week between treatments, showed that in table potato the economic net return was highest at 100% and 75% of the recommended dose, whereas in starch potato cultivars it was highest at 50% and 25% of the recommended dose.

The net financial result was calculated for 13 different scenarios. As expected, potato price and potato crop yield and quality were of the greatest importance. The price of fungicides affected net profits by between 167 and 656 € ha^{-1} depending on treatment intervals and dose.

These results challenge the way in which late blight is controlled in conventional potato farming today, especially in starch potatoes. We therefore propose investment in future years be based on the dose-range response in cultivars with differing host resistance to both PLB and PTB, and on forecasting and warning with respect to PLB- and PTB-control in different potato cultivars. We believe that such investment could be very valuable in optimizing the use of fungicides in potato cultivation.

Keywords: *Solanum tuberosum; Phytophthora infestans;* Net return; Plant protection; Fungicide

Introduction

The oomycete *Phytophthora infestans* (Mont.) de Bary which causes potato late blight (PLB) and potato tuber blight (PTB) can be very destructive if not controlled. For example, it can seriously reduce potato yield, both quantitatively and qualitatively [1-3]. Different fungicides are generally used for preventive control and must be applied repeatedly, often once a week, during the growing season to completely eliminate and control PLB and PTB [4-6].

Potato late blight (PLB) is the plant disease that contributed to the founding of plant pathology as a scientific discipline in the aftermath of the great disaster that PLB and potato tuber blight (PTB) caused primarily in Ireland but also in other European countries in the mid-1840s. The importance of this oomycete and the damage it can cause in terms of human suffering, hunger, disease and subsequent death, are well documented [7-11]. Since then, fungicides ranging from contact-acting agents to translaminar and systemic agents with excellent activity against PLB and PTB have been developed. Chemical control has been the rule in conventional potato cultivation for more than 60 years in countries that can afford it, and the costs associated with use of fungicides are relatively high. Nevertheless, relatively few large-scale economic estimates of this destructive plant disease have been made. PLB and PTB are probably regarded as so serious and threatening that economic analysis is not needed.

Financial calculations have been made in the US of the costs associated with the control of PLB during the difficult PLB year 1995 and subsequent years [12,13]. The analysis showed that these costs could be reduced by the application of integrated pest management (IPM), particular by using more resistant cultivars and forecasting and warning models, and by introducing sanitary measures [12-15]. In Sweden, financial estimates on the use or omission of fungicides against PLB and PTB have been made on a few occasions. Professor Jakob Eriksson, an eminent international authority in mycology and plant pathology in the late 1800s-early 1900s, gave a speech in 1891, less than 50 years after the Great Famine, entitled: Economic significance of plant diseases and measures that could and should be taken against them [7]. In this speech, he described the difficulties in making economic estimates of the damage caused by PLB, since it can range from 5%-10% to 60%-70% at different sites and cause considerable losses.

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The importance of carefully sorting and packaging of the potato grown in Sweden before sale was stressed in the early 1900s, not least in order to compete against imported potato of good quality from Germany, which even could be delivered to Stockholm with lower freight costs than potato from southern Sweden [16].

Åkerman [17] provided no figures on PLB and PTB costs, but attributed yield variations in potato between years mainly to PLB. In order to prevent fluctuations in tuber yield between years he recommended spraying with Bordeaux mixture (vitriol and lime). With the outbreak of World War II it became more important to get high tuber yield as countries faced possible food shortages. Åkerman [17] even went so far as to consider the introduction of mandatory spraying of potato crops. Lindblom [18] concluded that spraying with Bordeaux mixture, even in less severe PLB years, was economically justified.

In 1944, Karl Björling, a professor of plant pathology, summarised the economic importance of PLB as mean annual losses in growing crops of 10%-15% and losses in storage due to PTB in a similar magnitude. He also pointed out that losses in growing crops can reach 30% and more in some years, but in other years may be very small or non-existent. He estimated the returns from successful control of PLB and virus diseases to be 60-70 million SEK, or 6.7-7.8 million €, in the monetary value of that time [19].

One report dealing with PLB and economics was published in 1977 [20]. That author concluded that: "Economical calculations concerning Potato Blight are complicated. Calculations of damage can be simplified if the sum is regarded as being equal to the cost of chemical control. In table potatoes it is estimated to about 10 million Sw. crowns per year (1.1 million €), and 2 million crowns in factory potatoes (0.2 million €). The potential damage i.e. that which would be caused by abstaining from chemical control and by unchanged choice of varieties can be estimated at about 70 million crowns per year (7.8 million €) at a price of 0.40 crowns per kilo. This estimate is based on results from experiment data from 1957-1965, and includes harvest losses due to blight attacks both on leaves and tubers".

During the late 1970s, a series of reports issued by SLU's (The Swedish University of Agricultural Sciences) Department of Economics and Statistics placed an economic value on i) losses caused by pests, ii) various control measures, and iii) reduced use of pesticides [21-23]. Sundell's calculations were based heavily on Olofsson's experimental results and, consequently, he confirmed the very profitable results for the chemical control of PLB and PTB.

Haverkort et al. [24] estimated losses in the European Union (EU) due to PLB to be 900 million € year^{-1}. In the Netherlands with a total of 165 000 hectare (ha) year^{-1} of potato production, the total costs of late blight are estimated to about 125 million € year^{-1} or slightly more than 750 € ha^{-1}. Thus, costs in association with the control of PLB are of considerable economic importance in the Netherlands and other EU countries, and much would be gained by the use of durable resistant cultivars and thereby reduced use of fungicides [24].

Large amounts of fungicides are used in Europe and on other continents like America and Asia to prevent PLB and PTB infection [6,11,25]. Fungicides are very likely to be an important part in the fight against fungal diseases for many years to come, not least against PLB [26]. The prevailing opinion among many advisors and growers is that limiting and reducing the use of fungicides in terms of lowering the dose and prolonging the treatment interval would unnecessarily jeopardize potato tuber yield and its quality. Many potato growers therefore treat their fields routinely many times a season, with the first application a week or a few weeks before the potato foliage covers the aisles and the last treatment just before chemical desiccation, without taking any great account of the potato cultivar's resistance to PLB and PTB. Results from field trials show that the fungicide dose can be reduced without major impacts on either the efficacy against PLB and PTB or tuber yield [27-30].

Dose-response experiments are often performed by plant protection companies, as the results are needed in the documentation submitted to the authorities prior to approval of a product. National trial results from dose-response experiments are less common, but the need for such results is large, especially in the Integrated Pest Management (IPM) context.

During two periods, each lasting several years, we therefore carried out official dose-response experiments with the aim of investigating the economically optimal dose for control of PLB and PTB in potato cultivars with differing levels of resistance to PLB and PTB. It is also important to know how the profitability of production varies, with changing potato prices, with potato yield levels and with different costs of production factors. Therefore we tested these factors in different scenarios.

Materials and Methods

An economic analysis and evaluation was made of results from field trials with different cultivars, and with two to five different doses of fungicides against PLB and PTB, conducted in an earlier period (1993-1996) and in a more recent period (2010-2013).

Field trials

The field trials reported here were conducted in the manner described by Wiik [31]. The trials were located on good agricultural soils suitable for potato cultivation, at agricultural experimental stations and in farmers' fields. All cropping measures were largely conducted in the same manner as in conventional cultivation of potatoes. Untreated controls were included in all field trials, one in each of four replicates (I-IV). In addition, three untreated rows not sprayed with PLB-fungicides between replicates I and II and between replicates III and IV served as infection sources for PLB. Natural infection of PLB occurred in all field trials without artificial inoculation. Planting was done during late April to early June in all years and occurred on average in mid-May, or 133 days from January 1. The potatoes were harvested on average, in the beginning of October, or 276 days after January 1, giving 143 days from planting to harvest. Planting was done a few days later in the earlier period (1993-1996) than in the more recent period (2010-2013). Harvesting was almost two weeks later in the earlier period than in the more recent period.

Field trials 1993-1996

The earlier trial series included 22 field trials with table potato with the same experimental design in all trials, but the cultivars and fungicide varied [32-34]. The fungicide Shirlan (a.i. fluazinam 500 g/l) was used in 10 of the field trials, while Tattoo (a.i. mancozeb 302 g/l+propamocarb hydrochloride 248 g/l) was used in the remaining 12 field trials. In addition to the untreated control, the study plan included five doses (30, 45, 60, 75 and 100% of the recommended dose) at short treatment intervals or with approximately a week (on average 7.9 days) between treatments and four doses (45%, 60%, 75% and 100%) at long treatment intervals or with approximately two weeks (on average 14.3 days) between treatments. On average for the 22 trials, treatments were performed 9.7 times (7-12 times) at short intervals and 5.7 times (5-8 times) at long intervals. Two field trials were carried out in the same field at 11 sites, one with a susceptible cultivar and the other with a moderately resistant cultivar, i.e. giving a total of 22 field trials. Cultivar (cultivar, cv.) Bintje was used in 11 trials, cv. Hertha in 10 and cv. Matilda in 1. Bintje is a cultivar susceptible to PLB, while cv. Hertha and cv. Matilda were moderately resistant to PLB. Most of the field trials were located in southern Sweden, with 16 field trials in Skåne County within ~ 50 km from the town of Höör (55.931568, 13.546121, WGS84 decimal; latitude, longitude) and four in Holland County ~ 15 km south of Halmstad (55.669021, 12.866321). Two field trials were located in central Sweden at the same site ~ 15 km south of Uppsala (59.858178, 17.633915) in Uppland County.

Field trials 2010-2013

The more recent trial series included a total of 12 field trials [3], all performed close to Mosslunda (55.982538, 14.105415) about 10 km south of Kristianstad in Skåne County.

In 2010 two trials were performed, each with three cultivars: table potato cultivars Bintje, Ovatio and Andean Sunrise in one field trial, and starch potato cultivars Seresta, Kardal and Merano in the second. Among table potato cultivars, Bintje is very susceptible, Ovatio moderately resistant and Andean Sunrise very resistant to PLB. Among starch potato cultivars Seresta and Kardal are moderately resistant and Merano very resistant to PLB. Both these field trials were carried out in the same field. In addition to the untreated control, the study plan included four doses (25%, 50%, 75% and 100% of the recommended dose) of alternating applications of Revus (a.i. mandipropamid 250 g/l) or Ranman (ai cyazofamid 400 g/l). Treatment was performed 11 times in the table potato cultivar field trial and 12 times in the starch cultivar potato trial, at short intervals with on average 7.0 days (6-8) between treatments.

In 2011 two trials were carried out, each with two cultivars, table potato cultivars Bintje and Ovatio in one field trial and starch potato cultivars Seresta and Merano in the other. Both field trials were carried out in the same field. In addition to the untreated control the study plan included two doses (50% and 100% of the recommended dose) with Shirlan. Treatment was performed 11 times in both the table potato and the starch potato trials, at short intervals with on average 6.7 days (6-8) between treatments.

In 2012 four field trials were carried out, all in the same field and each with one cultivar: Bintje, Ovatio, Seresta and Merano. In addition to the untreated control, the study plan included two doses (50% and 100%) with Ranman Top (ai cyazofamid 14.8% of weight). Treatment was performed 11 and 12 times in the two table potato cultivar field trials and 13 times in both starch cultivar potato trials at short intervals with on average 6.9 days (usually 6-8 but 12 days once in one trial) between treatments.

In 2013 four field trials were carried out, all in the same field and each with one cultivar: Bintje, Sava, Seresta and Merano. In addition to the untreated control the study plan included three doses (25%, 50% and 100%) with Ranman Top. Treatment was performed 10 and 12 times in the two table potato cultivar field trials, and 12 and 13 times in the two starch cultivar potato trials, at short intervals with on average 7.0 days (usually 6-9 days but 3 and 12 days in one trial) between treatments (Table 1).

Disease assessment

An attack of PLB of 0.01% was taken to correspond to one blight-spot per 50 plants, 0.1% one blight-spot per plant, 1% up to 10 blight-spots per plant, 5% about 50 blight-spots per plant and 10% about 100 blight-spots per plant. For the results from the earlier period, the maximum attack of PLB (PLBMax) was used, i.e. the latest secure assessment. In addition, for the results from the recent period the Relative Area under Disease Progress Curve (RAUDPC) was used. Tuber samples from each plot (6 or 10 kg/ha corresponding to 50-200 tubers) taken at harvest were usually sorted into marketable fractions and PTB was assessed after a few months of storage.

Economics

The economic calculation for table potato largely followed a model we used in previous papers [33,35]:

$$U=[(Y-D)*N]-(cF+cA)$$

$$N=Z-(cP+cK+cH+cT+cS)$$

where U (€ ha^{-1}) is the net return, Y (ton ha^{-1}) is the potato tuber yield increase due to a fungicide treatment, D (ton ha^{-1}) is the yield loss due to wheel damage caused by spraying, N (€ ha^{-1}) is the net value ton^{-1} blight-free tubers, cF (€ ha^{-1}) is the cost of fungicide and cA (€ ha^{-1}) the costs of application of fungicides. The net value N is the tuber price Z (€ ton^{-1}) minus the cost of phosphorus (cP) and potassium (cK) losses from the field, harvest (cH), transport (cT) and storage (cS). The price of table potato ton^{-1} (Z) followed current prices 2013 for different fractions (Table 2, Scenario 1). The price of starch potato ton^{-1} followed an equation for 2013 from Lyckeby Starch, the only starch company in Sweden (pers. com. H Knutsson, Lyckeby Starch). The price (€) of 1 ton starch potato ha^{-1}=[2.9577*C (starch content)+0.0755]/9.00.

The results were initially calculated in Swedish crowns (SEK) and the conversion factor we used in this paper was 9.00 € for 100 SEK, a value that provides a relevant average over the years included in this study. In the previous papers we worked with cereals [33,35]. Calculations for table potato differ from those for cereals mainly in that the potato tuber crop is sorted into three fractions (<40 mm, 40-60 mm, >60 mm) that are sold at different prices. The basis for the calculations is shown in Table 2.

The net return was calculated for 13 scenarios (Sc1 – Sc13), that differed in terms of potato price, fungicide price and yield level (Tables 1 and 2). In the different scenarios, potato prices (current price minus 60% to current price plus 40%, Sc2-Sc4) were chosen due to realistic fluctuations and expectations of price changes during recent years, fungicide prices (minus 50% of current prices to plus 300% of current prices, Sc5-Sc9) due to national tax and contributions, and tuber yield (from 50% of current yield 150% to 50% of current yield in 25% increments) which is within the limits that we find possible.

Statistical methods

Statistical analysis (SPSS ver. 22.0) consisted of ANOVA followed by Tukey's test, and Pearson correlation [36]. Checks were carried out for normal distribution of the data and transformation of data was not needed. ANOVA was used to detect statistically significant differences between treatments in the field trials. Multiple comparisons were made with Tukey's honestly significant test. Different letters within columns in tables represent a significant difference of means at p=0.05 (Tables 3 and 4). To study the relationship between various parameters, such as potato late blight (PLB) at the last distinct assessment (PLBMax) and relative area under disease progress curve of late blight (RAUDPC), Pearson correlation were used. No statistics were carried out on economics. The lines in the Figures 1-6 should only be used as a means to identify the different points of the different scenarios and indicates no connection between points in a scenario.

Scenario 1 (Sc1):	Calculated based on the current table potato price, yield level and fungicide prices. Main scenario
Scenario 2 (Sc2):	Calculated from a very low potato price, current price minus 60%
Scenario 3 (Sc3):	Calculated from a low potato price, current price minus 40%
Scenario 4 (Sc4):	Calculated from a high potato price, current price plus 40%
Scenario 5 (Sc5):	As Sc1 but with a price of 50% of the current price of fungicides
Scenario 6 (Sc6):	As Sc1 but with a price of 150% of the current price of fungicides
Scenario 7 (Sc7):	As Sc1 but with a price of 200% of the current price of fungicides
Scenario 8 (Sc8):	As Sc1 but with a price of 250% of the current price of fungicides
Scenario 9 (Sc9):	As Sc1 but with a price of 300% of the current price of fungicides
Scenario 10 (Sc10):	As Sc1 but with a reduction in tuber yield, i.e. 50% of the current tuber yield
Scenario 11 (Sc11):	As Sc1 but with a reduction in tuber yield, i.e. 75% of the current tuber yield
Scenario 12 (Sc12):	As Sc1 but with an increase in tuber yield, i.e. 125% of the current tuber yield
Scenario 13 (Sc13):	As Sc1 but with an increase in tuber yield, i.e. 150% of the current tuber yield

Table 1: Designation and economic conditions for different scenarios, Sc1 main scenario, Sc2-Sc4 potato prices, Sc5-Sc9 fungicide prices and Sc10-Sc13 potato tuber yield levels.

Scenarios	**Table potato price[a]**			**Fungicide costs**					**Appl.[b]**	**Sort.[b]**	**Transp.[b]**	**P[c]**	**K[c]**
	<40 mm	**40-60 mm**	**>60 mm**	**Shirlan**	**Ranman**	**Revus**	**Tattoo**	**Amistar**				**Loss**	**Loss**
	€ ton^{-1}	**€ ton^{-1}**	**€ ton^{-1}**	**€ l^{-1}**	**€ l^{-1}**	**€ l^{-1}**	**€ l^{-1}**	**€ l^{-1}**	**€ ha^{-1}**	**€ ton^{-1}**	**€ ton^{-1}**	**€ ton^{-1}**	**€ ton^{-1}**
Sc 1	222	278	222	53	50	40	126	41	16	28	5.2	1.2	3.1
Sc 2	89	111	89	53	50	40	126	41	16	28	5.2	1.2	3.1
Sc 3	133	167	133	53	50	40	126	41	16	28	5.2	1.2	3.1
Sc 4	311	389	311	53	50	40	126	41	16	28	5.2	1.2	3.1
Sc 5	222	278	222	26	25	20	63	21	16	28	5.2	1.2	3.1
Sc 6	222	278	222	79	76	60	189	62	16	28	5.2	1.2	3.1
Sc 7	222	278	222	105	101	80	252	83	16	28	5.2	1.2	3.1
Sc 8	222	278	222	132	126	100	315	104	16	28	5.2	1.2	3.1
Sc 9	222	278	222	158	151	120	378	124	16	28	5.2	1.2	3.1
Sc 10	222	278	222	53	50	40	126	41	16	28	5.2	1.2	3.1
Sc 11	222	278	222	53	50	40	126	41	16	28	5.2	1.2	3.1
Sc 12	222	278	222	53	50	40	126	41	16	28	5.2	1.2	3.1
Sc 13	222	278	222	53	50	40	126	41	16	28	5.2	1.2	3.1

[a]The price of starch potato per ton follows an equation for 2013 from Lyckeby Starch (pers. com. H Knutsson, Lyckeby Starch)
The price (€) of 1 ton starch potato ha^{-1}=[2.9577*C (starch content)+0.0755]/9.00
[b]Application costs, sorting costs and transport and storage costs
[c]P and K loss=the cost of loss of phosphorus (P) and potassium (K) from the field, a loss associated with the disposal of the potato harvest

Table 2: Economics of 13 scenarios (Sc1-Sc13) with different potato tuber prices (€ ton^{-1}) and different treatment costs associated with spraying (€ l^{-1}, € ha^{-1}, € ton^{-1}). See Table 1 for designations of scenarios (Sc1-Sc13).

Dose%/ interval	**Potato late blight at maximum attack (PLBMax), %[a]**						**Potato tuber blight (PTB), wt%[a]**					
	SuscC	**ModRC**	**LowPLB**	**HighPLB**	**Shirlan**	**Tattoo**	**SuscC**	**ModRC**	**LowPLB**	**HighPLB**	**Shirlan**	**Tattoo**
Untreated	56.4 a	29.7 a	10.5 a	75.6 a	39.9 a	45.6 a	9.4 a	1.7 a	2.6 a	8.6 a	5.6 a	5.5 a
100/short	0.2 b	0.1 b	0.1 b	0.2 b	0.1 b	0.1 b	3.7 a	2.0 a	1.8 a	3.9 a	0.9 b	4.4 a
75/short	0.6 b	0.1 b	0.1 b	0.6 b	0.1 b	0.5 b	3.9 a	1.3 a	1.2 a	4.0 a	0.3 b	4.5 a
60/short	0.8 b	0.1 b	0.1 b	0.8 b	0.2 b	0.7 b	2.5 a	1.4 a	1.3 a	2.6 a	0.3 b	3.3 a
45/short	1.2 b	0.2 b	0.2 b	1.3 b	0.7 b	0.7 b	2.5 a	1.3 a	1.1 a	2.6 a	0.4 b	3.0 a
30/short	2.2 b	0.2 b	0.2 b	2.2 b	0.7 b	1.6 b	3.1 a	1.4 a	1.4 a	3.1 a	0.5 b	3.7 a
100/long	1.5 b	0.1 b	0.1 b	1.5 b	0.2 b	1.3 b	3.0 a	1.5 a	1.4 a	3.1 a	0.1 b	4.0 a
75/long	3.2 b	0.1 b	0.1 b	3.2 b	0.2 b	2.8 b	3.6 a	1.6 a	1.4 a	3.8 a	0.5 b	4.4 a
60/long	3.8 b	0.3 b	0.1 b	4.0 b	1.3 b	2.7 b	2.3 a	1.2 a	1.0 a	2.5 a	0.4 b	2.9 a
45/long	8.6 b	0.4 b	0.2 b	8.8 b	1.9 b	6.6 b	6.0 a	2.1 a	1.8 a	6.3 a	0.9 b	6.7 a
no. trials	11	11	11	11	10	12	11	11	11	11	10	12

[a] Tukey's honestly significant test. Different letters within columns in tables represent a significant difference of means at p=0.05

Table 3: Potato late blight (PLB) at the last distinct assessment (%, PLBMax) and tuber blight (wt%, PTB) in susceptible cultivars (SuscC) and in moderately resistant cultivars (ModRC), in those field trials with the lowest attack by PLB (<33% PLB in the untreated control, LowPLB) and those with the highest attack of PLB (>33% PLB in the untreated control, HighPLB) and in those treated with either the fungicide Shirlan or the fungicide Tattoo. Data from 22 field trials in 1993-1996.

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Dose%/ interval	Blight-free unsorted tuber yield[a], ton ha^{-1}						Net return, € ha^{-1}					
	SuscC	ModRC	LowPLB	HighPLB	Shirlan	Tattoo	SuscC	ModRC	LowPLB	HighPLB	Shirlan	Tattoo
Untreated	45.5 b	46.6 a	45.9 a	46.2 b	45.0 b	46.9 b	10839	11072	10942	10969	10703	11166
100/short	55.4 a	49.9 a	48.8 a	56.5 a	52.1 a	53.1 a	12195	10851	10679	12367	11566	11487
75/short	54.2 a	51.8 a	50.4 a	55.7 a	53.1 a	52.9 a	12013	11383	11128	12268	11845	11575
60/short	54.7 a	49.6 a	49.1 a	55.2 a	51.3 a	52.9 a	12174	10951	10891	12234	11463	11646
45/short	53.4 a	49.9 a	48.9 a	54.4 a	51.6 a	51.6 a	11935	11054	10886	12103	11575	11427
30/short	53.3 a	49.5 a	48.5 a	54.2 a	51.6 a	51.2 a	11969	11016	10871	12114	11595	11406
100/long	52.9 a	48.9 a	48.0 a	53.8 a	50.3 a	51.4 a	12001	11000	10846	12155	11472	11524
75/long	52.7 a	51.2 a	48.6 a	55.3 a	52.3 a	51.6 a	12000	11596	11061	12535	11968	11657
60/long	54.4 a	51.1 a	50.3 a	55.1 a	52.3 a	53.0 a	12426	11603	11489	12540	11978	12045
45/long	51.6 a	49.3 a	48.1 a	52.8 a	50.2 a	50.7 a	11827	11222	11003	12046	11499	11546
no. trials	11	11	11	11	10	12	11	11	11	11	10	12

[a] Tukey's honestly significant test. Different letters within columns in tables represent a significant difference of means at p=0.05

Table 4: Blight free unsorted tuber yield (ton ha^{-1}) and net return (€ ha^{-1}) in susceptible cultivars (SuscC) and in moderately resistant cultivars, (ModRC) in those field trials with the lowest attack by PLB (<33% PLB in the untreated control, LowPLB) and those with the highest attack of PLB (>33% PLB in the untreated control, HighPLB) and in those treated with either the fungicide Shirlan or the fungicide Tattoo. Data from 22 field trials in 1993-1996.

Results

Potato late blight (PLB) was effectively controlled in susceptible (SuscC) and moderately resistant cultivars (ModRC) during the early period, 1993-1996 (Table 3). However, in susceptible cultivars (SuscC) and during severe attacks of late blight (HighPLB) the effect against PLB was weakened at lower doses and longer intervals. A more or less pronounced dose response against PLB can be seen in Table 3, less in moderately resistant cultivars and at lower attack of PLB (LowPLB). The effects of the two fungicides Shirlan and Tattoo against PLB exhibited the corresponding dose-response. The effect at the recommended dose and short intervals against PLB was >99%, but the effect against tuber rot was poor and not statistically significant (Table 3).

On average, blight-free unsorted tuber yield was high in the untreated control, about 45 ton ha^{-1} (Table 4). No statistically significant differences in tuber yield were found between different treatments in these early field trials. The increase in tuber yield due to treatment in susceptible cultivars and in those field trials with the highest attacks of PLB was on average 8.1 and 8.6 ton ha^{-1}, respectively, with a variation from 6.1 to 10.3 ton ha^{-1} due to dose and interval. Tuber yield increase due to treatment in moderately resistant cultivars and in those field trials with the lowest attack of PLB was on average 3.5 and 3.1 ton ha^{-1}, respectively, with a variation from 2.1 to 5.2 ton ha^{-1} due to dose and interval. Overall, the highest tuber yield increase was obtained at the highest (recommended) dose of 100% and at short treatment intervals in field trials with susceptible cultivars and the highest attack of PLB. However, in field trials with moderately resistant cultivars and low attack of PLB, the highest tuber yield increase was obtained at 75% of the recommended dose applied at short intervals. On average, blight-free unsorted tuber yield was somewhat higher in field trials treated with Shirlan than those treated with Tattoo, but as these results come from different sites they are not directly comparable. There were no statistically significant differences between blight-free tuber yields in these field trials, not even between untreated control and treated plots (Table 4). On average, the economic net return (according to the definition in Materials and Methods) was >10 000 € ha^{-1} in the untreated control. The economic net return was highest at 60% fungicide dose and long treatment interval, independent of cultivar and the level of the attack of PLB. Net return due to treatment in susceptible cultivars and in those field trials with the highest attacks of PLB was on average 1221 and 1294 € ha^{-1}, respectively, with a variation from 988 to 1572 € ha^{-1} due to dose and interval (Table 4, columns SuscC and HighPLB). Tuber yield increase due to treatment in moderately resistant cultivars and in those field trials with the lowest attack of PLB was on average 114 and 41 € ha^{-1}, respectively, with a variation from -264 to 546 € ha^{-1} due to dose and interval (Table 4, columns ModRC and LowPLB). The highest net return was obtained for the 60% dose applied at long intervals to susceptible cultivars, to moderately resistant cultivars, at high and at low attack of PLB and in field trials treated with either Shirlan or Tattoo (Table 4).

During the early trial period potato prices had a huge influence on the net return, as expected (Figure 1). The difference was almost 15000 € ha^{-1} between scenario 2 (Sc2), with a very low potato price, and Sc4, with a high potato price. Compared with the current potato price, giving a net return of 11000-12000 € ha^{-1}, a very low potato price (minus 60%) gave a net return of 3000-4000 € ha^{-1} and a low potato price (minus 40%) a net return of about 6000 € ha^{-1}. Compared with the current potato price, a high potato price gave an additional 5000 € ha^{-1}.

In the main scenario (Sc1) with susceptible cultivar Bintje the net return for the best treatment (60/long) was 1588 € ha^{-1}. At a very low potato price (-60%, Sc2), a low potato price (-40% Sc3) and a high potato price (+ 40%, Sc4) the corresponding net return was 330, 749 and 2426 € ha^{-1}, respectively. In the main scenario (Sc1) with the moderately resistant cultivars Hertha and Matilda the net return for the best treatment (60/long) was 530 € ha^{-1}. At a very low potato price (-60%, Sc2), a low potato price (-40% Sc3) and a high potato price (+ 40%, Sc4) the corresponding net return was 4, 180 and 880 € ha^{-1}, respectively.

Yield level also had a great influence on the net return (Figure 2). The difference was about 12 000 € ha^{-1} between Sc10 with half yield compared with the current Sc 13 with a 150% increase in tuber yield. Compared with the current potato price giving a net return of 11000-12000 € ha^{-1}, a 50% reduction of the current tuber yield gives 5000-6000 € ha^{-1} and a 25% reduction 8000-9000 € ha^{-1}. At the current potato price, 125 and 150% higher tuber yield levels than the current level gave an additional 3000 and 7000 € ha^{-1}, respectively. The net return for the best fungicide treatment in the susceptible cultivar Bintje increased at higher tuber yield level in Sc10S, Sc11S, Sc1S, Sc12S and Sc13S, by 683, 1135, 1588, 2040 and 2493 € ha^{-1}, respectively. The net return in the moderately resistant cultivars Hertha and Matilda was not as much affected by the best fungicide treatment in Sc10R, Sc11R, Sc1R, Sc12R and Sc13R, giving 154, 342, 530, 719 and 907 € ha^{-1}, respectively.

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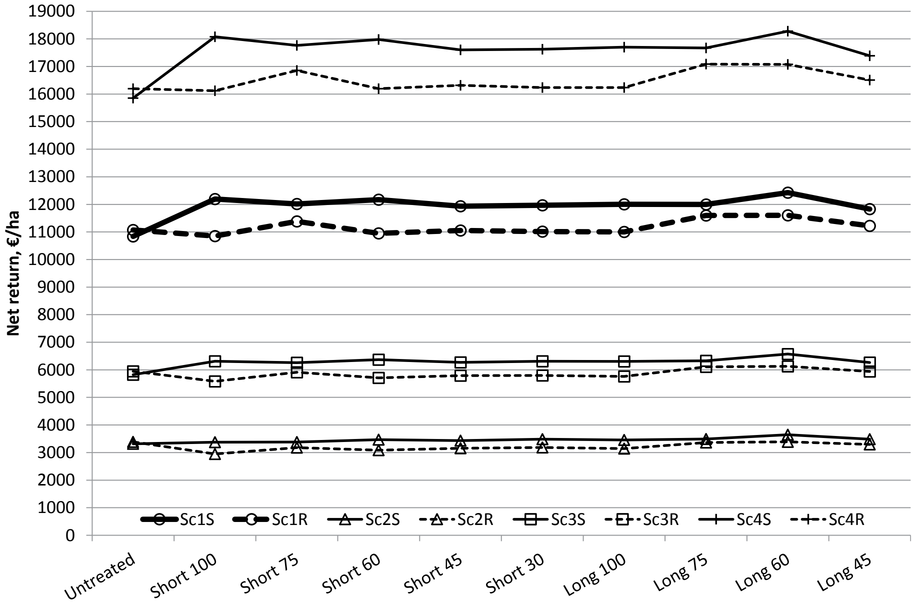

Figure 1: Net return (€ ha-1) 1993-1996 in scenarios with different potato prices: Sc1, Sc2, Sc3 and Sc4 in susceptible (S) and moderately resistant cultivars (R). The lines in the figure should only be used as a means to identify the different points of the different scenarios and indicates no connection between points in a scenario. Main scenarios, Sc1S and Sc1R, are highlighted with bold lines, scenarios with susceptible cultivars with solid lines and moderately resistant cultivars with broken lines.

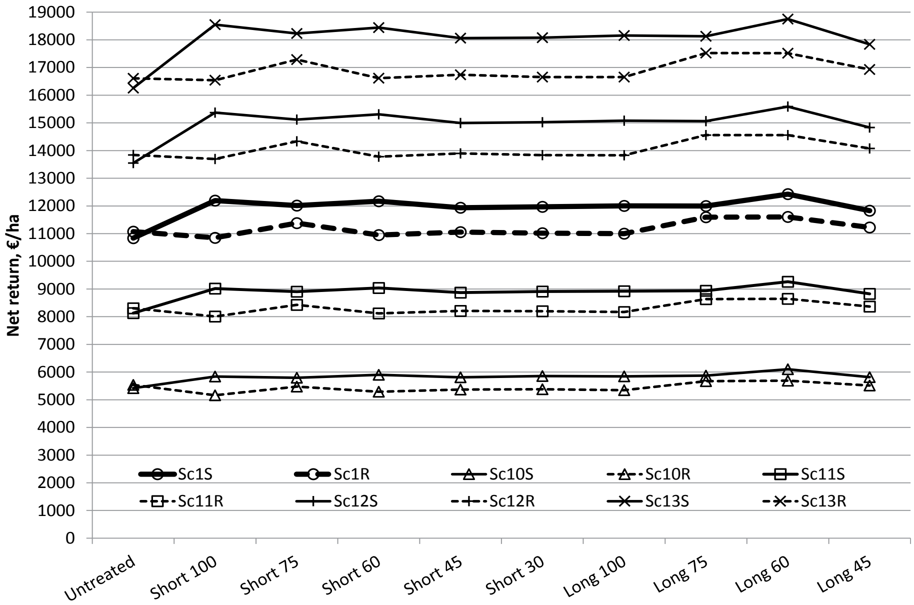

Figure 2: Net return (€ ha-1) 1993-1996 in scenarios with different potato tuber yield levels: Sc10, Sc11, Sc1, Sc12 and Sc13 in susceptible (S) and moderately resistant cultivars (R). The lines in the figure should only be used as a means to identify the different points of the different scenarios and indicates no connection between points in a scenario. Main scenarios, Sc1S and Sc1R, are highlighted with bold lines, scenarios with susceptible cultivars with solid lines and moderately resistant cultivars with broken lines.

The net return was of course negatively influenced by a higher fungicide price (Figure 3). The net return for the best fungicide treatment in the susceptible cultivar Bintje decreased at higher fungicide costs in Sc5S, Sc1S, Sc6S, Sc7S, Sc8S and Sc9S, from 1655, 1588, 1520, 1453, 1385 to 1318 € ha^{-1}, respectively. The net return for the best fungicide treatment in the moderately resistant cultivars Hertha and Matilda decreased at higher fungicide cost in Sc5R, Sc1R, Sc6R, Sc7R, Sc8R and Sc9R, from 598, 530, 463, 396, 328 to 261 € ha^{-1}, respectively.

During the first year, 2010, of the recent trial period PLB measured as PLBMax was controlled by all four fungicide treatments, i.e. recommended dose, 75%, 50% and 25% of recommended dose (Table 5). However, with the highest dose the average effect against PLB compared to the untreated control was ≥ 99% in both cv. Bintje and Ovatio, but at the lowest dose 95% and 97%, respectively. In starch potato the corresponding average effect against PLB of all four doses compared to the untreated control was ≥ 99% in all three cultivars, except for cv. Seresta with the two lowest doses, however still ≥ 98%.

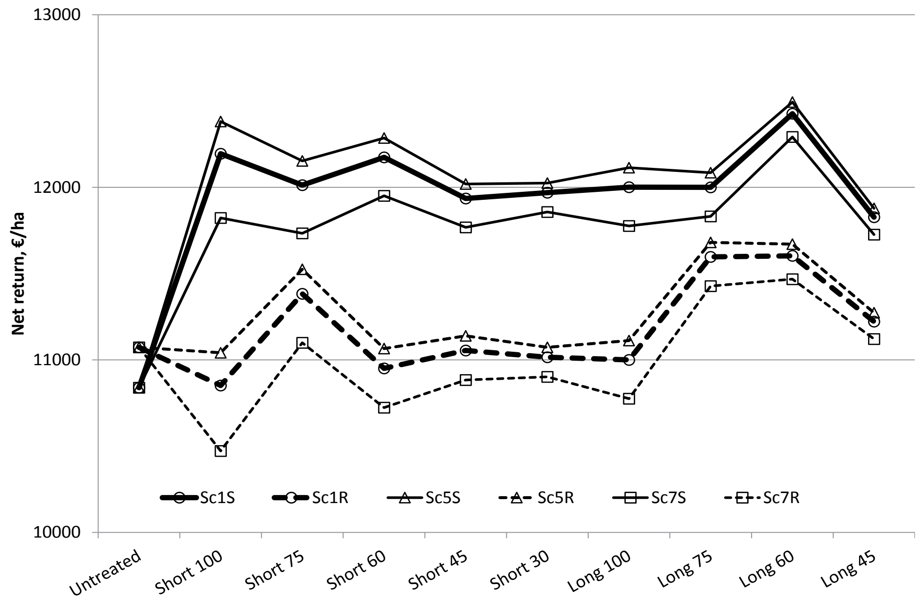

Figure 3: Net return (€ ha^{-1}) 1993-1996 in scenarios with different fungicide costs: Sc1, Sc5 and Sc7 in susceptible (S) and moderately resistant cultivars (R). The lines in the figure should only be used as a means to identify the different points of the different scenarios and indicates no connection between points in a scenario. Scenarios with susceptible cultivars are highlighted with solid lines, e.g. main scenario Sc1S. Moderately resistant cultivars are highlighted with broken lines, e.g. scenario Sc1R.

When RAUDPC was used instead of PLBMax as a measure of the attack, the corresponding average effect as just described above of the different treatments was worse, e.g. with the three highest doses the average effect against PLB compared to the untreated control was 83-85% in cv. Bintje and 92% in cv. Ovatio, but at the lowest dose 82% and 87%, respectively, and 75-76% in starch cultivars at the highest doses, but at the lowest dose 70%-76%.

The incidence of potato tuber blight (PTB) was low during 2010 and was just over 1% by weight in the most affected cultivar, cv. Merano. The yield increase was between 15-20 tons ha^{-1} at any dose in both table potato and starch potato. The net return in table potato was highest for the 75% of recommended dose or recommended dose treatments, and in starch potato for the 25% or 50% of recommended dose treatments. The net return was four- to five-fold higher in table potato than in starch potato (Table 5).

The effect against PLB measured as PLBMax compared to the untreated control was not fully effective for the two fungicide treatments (recommended dose and 50% of recommended) used in the field trials during 2011 and 2012 in either table or starch potato (Table 6). In table potato the effect was on average approximately 90% with the two doses, while in starch potato the effect was <65%. Halving the dose resulted in somewhat lower efficacy in table potato and clearly worse efficacy in starch potato. When RAUDPC was used instead of PLBMax as a measure of attack, the effect of the different treatments was much worse, about 40% in table potato and approximately <50% in starch potato. The incidence of PTB in the untreated control was high during 2011 and 2012 in the most affected cultivar, cv. Merano. The yield increase was on average approximately 10 tons ha^{-1} at the two doses in table potato and somewhat lower in starch potato. The net return in table potato was highest with the recommended dose and in starch potato with 50% of the recommended dose. The net return was significantly higher in table potato, in the order of 1500-2000 EUR ha^{-1}, than in starch potatoes where it was at least 10-fold lower, i.e. in the order of 50-150 € ha^{-1} (Table 6).

The effect against PLB (PLBMax) by the three different treatments (recommended dose, 50% and 25% of recommended dose) was not fully effective during the last year, 2013, although it was better than during the previous two years (Table 7). In table potato the effect was in the order of 85%-96% and in starch potato in the order of 85%-90%. The dose-response effect was apparent but relatively weak in both table potato and starch potato. When RAUDPC was used instead of PLBMax as a measure of attack, the effect of the different treatments was worse in both table potato and starch potato. The attack by PTB was also high in 2013 in cv. Merano. The yield increase was in the order of 10-20 tons ha^{-1} in table potato, with a clear dose-response. In starch potato the yield increase was ~ 9 ton ha^{-1}, independent of the doses. The net return in table potato was highest with the recommended dose, and in starch potato with 25% of the recommended dose. The net return was several-fold higher in table potato than in starch potato (Table 7).

During 2010 the potato price had as expected a huge influence on the net return (Figure 4). The difference in table potato treated plots was approximately 13 000 € ha^{-1} between scenario 2 (Sc2) with a very low potato price (-60%), and Sc4, with a high potato price (+40%). A high potato price (+40%, Sc4) and a low potato price (-40%, Sc3) gave a net return of 5 000 € ha^{-1} more or less in comparison with the current table potato price (Sc1), which gave a net return for plots treated with fungicides of about 11 000 € ha^{-1}. The difference in starch potato treated plots was approximately 3 000 € ha^{-1} between scenario 2 (Sc2), with a very low potato price (-60%), and Sc4, with a high potato price (+40%). A high potato price (+40%, Sc4) and a low potato price (-40%, Sc3) gave a net return of 1 000 € ha^{-1} more or less in comparison with the current starch potato price, which gave a net return of somewhat more than 2 000 € ha^{-1}. The net return decreased very little with a reduction in the dose.

During 2010-2013 the potato price again had the expected huge influence on the net return (Figure 5). The difference in table potato treated plots was approximately 14000 € ha^{-1} between scenario 2 (Sc2),

	Table potato cultivars			Starch potato cultivars		
	Bintje	Ovatio	Andean Sunrise	Seresta	Kardal	Merano
PLBMax, %[b]						
Untreated	100.00 a	92.20 a	1.30 a	95.90 a	78.80 a	36.00 a
Dose 100%	0.50 b	0.21 b	0.05 b	0.81 b	0.35 b	0.04 b
Dose 75%	1.19 b	0.65 b	0.11 b	0.85 b	0.33 b	0.04 b
Dose 50%	1.25 b	0.78 b	0.09 b	1.15 b	0.14 b	0.06 b
Dose 25%	5.50 b	2.88 b	0.45 b	1.50 b	0.53 b	0.18 b
RAUDPC[b]						
Untreated	0.71 a	0.38 a	0.08 a	0.69 a	0.62 a	0.50 a
Dose 100%	0.11 b	0.03 b	0.03 b	0.17 b	0.15 b	0.12 b
Dose 75%	0.12 b	0.03 b	0.02 b	0.17 b	0.15 b	0.12 b
Dose 50%	0.11 b	0.03 b	0.03 b	0.14 b	0.17 b	0.12 b
Dose 25%	0.13 b	0.05 b	0.03 b	0.21 b	0.16 b	0.12 b
Tuber blight, wt%						
Untreated	0.3 a	0.0 a	0.6 a	0.1 a	0.0 a	1.2 a
Dose 100%	0.0 a	0.0 a	0.0 a	0.4 a	0.0 a	0.0 a
Dose 75%	0.0 a	0.0 a	0.0 a	0.0 a	0.0 a	0.0 a
Dose 50%	0.0 a	0.0 a	0.0 a	0.0 a	0.0 a	0.0 a
Dose 25%	0.0 a	0.0 a	0.0 a	0.0 a	0.0 a	0.0 a
Tuber yield, ton ha^{-1}						
Untreated	33.4 b	37.7 b	34.6 b	27.1 b	37.7 b	31.3 b
Dose 100%	59.0 a	57.5 a	42.3 a	50.2 a	53.1 a	46.3 a
Dose 75%	57.1 a	59.6 a	42.3 a	50.3 a	50.1 a	45.0 a
Dose 50%	57.6 a	58.2 a	39.1 ab	51.7 a	50.6 a	45.5 a
Dose 25%	55.9 a	54.5 a	40.6 a	48.1 a	50.8 a	47.4 a
Net return, € ha^{-1}						
Untreated	7368	8489	7737	1407	1969	1810
Dose 100%	12147	11920	8618	2366	2549	2040
Dose 75%	11805	12336	8634	2477	2402	1999
Dose 50%	12034	12131	8059	2616	2520	2157
Dose 25%	11672	11317	8462	2421	2558	2396

[a] Tukey's honestly significant test. Different letters within columns for each variable in tables represent a significant difference of means at p=0.05
[b] PLBMax: The Maximum Attack of Potato Late Blight; RAUDPC: Relative Area Under Disease Progress Curve

Table 5: Biological and economic results from two field trials carried out in 2010, one with the table potato cultivars Bintje, Ovatio and Andean Sunrise and one with the starch potato cultivars Seresta, Kardal and Merano. For statistics see footnote [a].

with a very low potato price, and Sc4, with a high potato price. A high potato price (+40%, Sc4) and a low potato price (-40%, Sc3) gave a net return of about 6000 € ha^{-1} more or less in comparison with the current table potato price (net return for treated plots of approximately 12000 € ha^{-1}). The difference in starch potato treated plots was somewhat more than 3 000 € ha^{-1} between scenario 2 (-60%, Sc2), and scenario 4 (+40%, Sc4). At a high potato price (+40%, Sc4) and low potato price (-40%, Sc3), the net return was about 1 000 € ha^{-1} more or less in comparison with the current starch potato price (~ 2 000 € ha^{-1}). Halving the dose of fungicides in starch potato cultivation did not affect profitability, but would do so at present and higher price levels in table potato (Figure 5).

The net return was much more dependent on the potato price (Figure 5) and the potato tuber yield level than the price of late blight fungicides (Figure 6).

Discussion and Conclusion

The profitability of a potato crop is determined by many factors. Conditions conducive to growth, i.e. healthy seed, a suitable site for potato growing, optimal tillage and soil conditions, weed control, access to water, available plant nutrients, pest management, good conditions at harvesting, etc., determine both the biological and economic outcome. Since PLB is a very serious plant disease in conventional potato cultivation, requiring high financial outlay in terms of fungicides and labour for repeated treatment operations, we opted to focus on this aspect of potato cultivation, without forgetting other aspects that are very costly in this crop. Potato growers' problems with PLB have not diminished, despite excellent fungicides in recent decades. On the contrary, PLB is occurring earlier and sexual reproduction is allowing great genetic variation in leaf blight populations, not least in Sweden [2,6,31,37-39]. We investigated the biological and economic outcome during two periods, an early (1993-1996) and a recent (2010-2013), of different treatment intervals and doses of fungicides against PLB and PTB in table potato cultivars and starch potato cultivars with differing susceptibility to PLB and PTB.

When using repeated chemical control of PLB with fungicides, the intention is 100% control or zero tolerance. However, it is our experience that in recent years it has become increasingly difficult to overcome PLB, despite increasing the number of fungicide treatments. The results presented in this paper show that the effects of chemical control against PLB were clearly better in the earlier trial period (more than 99% effect) than in the recent period (<65%-90% effect). The average effect against PLB of fungicide treatment at short interval and 100% dose in the susceptible cv. Bintje during the early period 1993-1996 was very high (99.6%) but the effect decreased with increasingly

	Table potato cultivars				Starch potato cultivars			
	Bintje	**Bintje**	**Ovatio**	**Ovatio**	**Seresta**	**Seresta**	**Merano**	**Merano**
	2011	2012	2011	2012	2011	2012	2011	2012
PLBMax, %[b]								
Untreated	80.75 a	96.25 a	25.25 a	60.75 a	85.00 a	46.25 a	14.75 a	0.07 a
Dose 100%	14.00 b	5.58 b	3.95 b	0.04 b	23.00 b	27.25 b	2.13 b	0.03 a
Dose 50%	19.25 b	6.25 b	8.03 b	0.31 b	41.00 b	28.75 b	4.88 b	0.03 a
RAUDPC[b]								
Untreated	0.74 a	0.54 a	0.61 a	0.37 a	0.46 a	0.39 a	0.16 a	0.13 a
Dose 100%	0.57 b	0.21 b	0.41 b	0.05 b	0.19 c	0.27 b	0.05 b	0.08 b
Dose 50%	0.59 b	0.24 b	0.48 b	0.05 b	0.27 b	0.28 b	0.07 b	0.08 b
Tuber blight, wt%								
Untreated	0.0 a	0.8 a	0.0 a	0.0 a	0.0 a	3.1 a	24.3 a	16.6 a
Dose 100%	0.7 a	0.0 a	0.0 a	0.0 a	0.4 a	0.0 b	16.3 a	0.0 b
Dose 50%	0.8 a	0.0 a	0.0 a	0.0 a	0.0 a	0.0 b	26.5 a	0.0 b
Tuber yield, ton ha^{-1}								
Untreated	25.3 b	46.0 b	35.1 b	54.2 a	32.3 b	51.2 a	26.2 b	31.9 b
Dose 100%	37.2 a	60.2 a	47.2 a	65.4 a	43.0 a	51.0 a	33.2 a	46.4 a
Dose 50%	35.1 a	58.7 a	44.5 a	66.0 a	39.3 a	52.1 a	32.7 a	47.5 a
Net return, € ha^{-1}								
Untreated	5507	10314	7972	12279	1846	3179	1446	2075
Dose 100%	7634	12287	9870	13748	2123	2743	1474	2375
Dose 50%	7259	12164	9375	13989	1997	3026	1521	2682

[a] Tukey's honestly significant test. Different letters within columns for each variable in tables represent a significant difference of means at p = 0.05.
[b] PLBMax = the maximum attack of potato late blight, RAUDPC = Relative area Under Disease Progress Curve.

Table 6: Biological and economic results from six field trials carried out in 2011 and 2012, one with the table potato cultivars Bintje and Ovatio and one with the starch potato cultivars Seresta and Merano in 2011 and four with each cultivar in the same field in 2012. For statistics see footnote[a].

	Table potato cultivars		Starch potato cultivars	
	Bintje	**Sava**	**Seresta**	**Merano**
PLBMax, %[b]				
Untreated	92.75 a	50.75 a	79.00 a	17.00 a
Dose 100%	3.88 b	1.49 b	8.00 b	0.53 b
Dose 50%	6.00 b	2.58 b	9.25 b	1.08 b
Dose 25%	16.75 b	5.88 b	11.50 b	1.83 b
RAUDPC[b]				
Untreated	0.50 a	0.38 a	0.31 a	0.09 a
Dose 100%	0.22 cd	0.08 c	0.07 b	0.01 b
Dose 50%	0.25 bc	0.12 c	0.08 b	0.01 b
Dose 25%	0.30 b	0.18 b	0.09 b	0.02 b
Tuber blight, wt%				
Untreated	2.3 a	0.9 a	0.0 a	9.6 a
Dose 100%	0.6 a	0.0 a	0.0 a	0.0 b
Dose 50%	0.5 a	0.2 a	0.0 a	0.0 b
Dose 25%	1.5 a	0.0 a	0.0 a	0.0 b
Tuber yield, ton ha^{-1}				
Untreated	48.5 b	61.6 a	55.6 b	45.9 a
Dose 100%	66.2 a	80.7 a	65.6 a	54.6 a
Dose 50%	62.3 a	75.8 a	63.2 a	54.7 a
Dose 25%	61.2 a	69.6 a	64.9 a	54.1 a
Net return, € ha-1				
Untreated	11085	13990	3562	3137
Dose 100%	14171	17132	3700	2961
Dose 50%	13494	16245	3689	3204
Dose 25%	13184	15082	3880	3207

[a] Tukey's honestly significant test. Different letters within columns for each variable in tables represent a significant difference of means at p=0.05
[b] PLBMax: The Maximum Attack of Potato Late Blight; RAUDPC: Relative Area Under Disease Progress Curve

Table 7: Biological and economic results from four field trials carried out in 2013, with one of each cultivar, Bintje, Ovatio, Seresta and Merano, in the same field. For statistics see footnote [a].

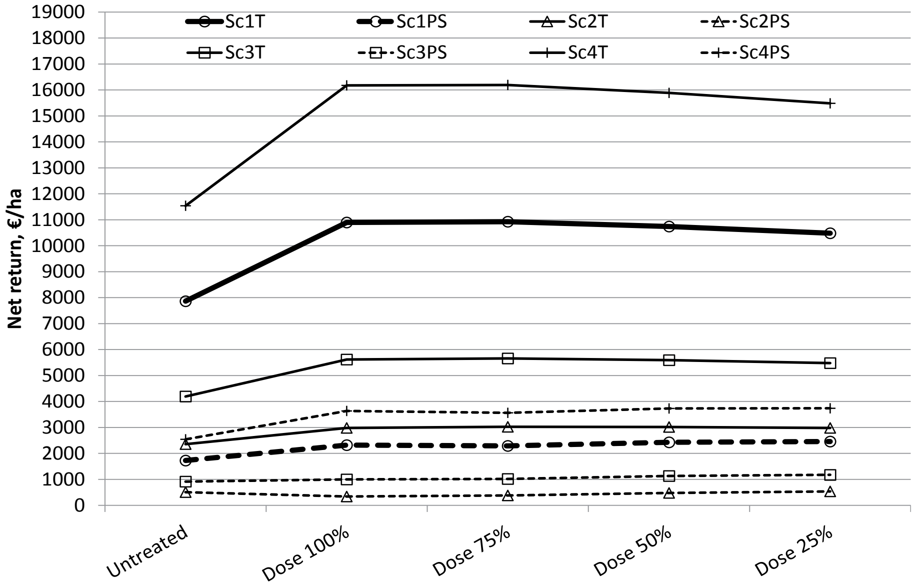

Figure 4: Net return (€ ha^{-1}) 2010 in scenarios with different potato prices: Sc1, Sc2, Sc3 and Sc4 in table potato (T) and starch potato (PS). The lines in the figure should only be used as a means to identify the different points of the different scenarios and indicates no connection between points in a scenario. Main scenarios, Sc1T and Sc1PS, are highlighted with bold lines, scenarios with susceptible cultivars with solid lines and moderately resistant cultivars with broken lines.

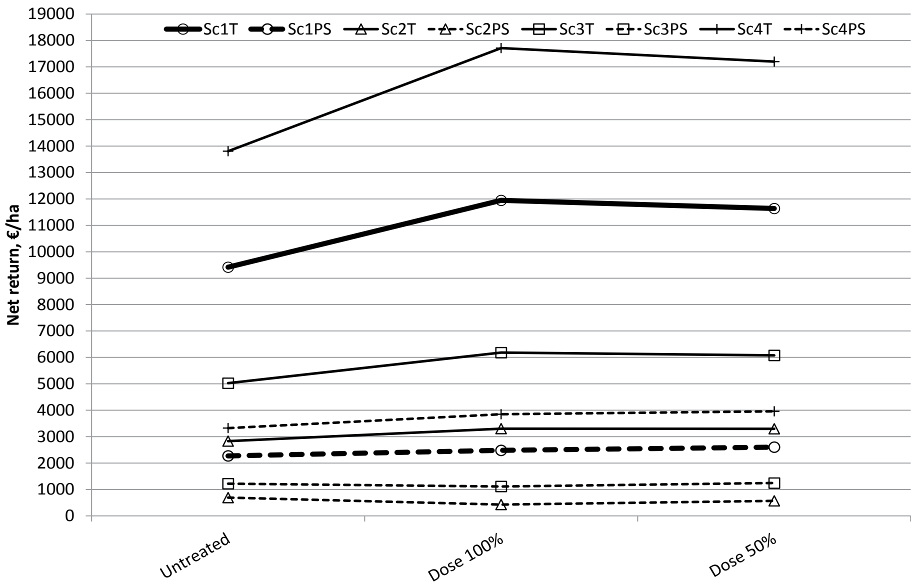

Figure 5: Net return (€ ha^{-1}) 2010-2013 in scenarios with different potato prices: Sc1, Sc2, Sc3 and Sc4 in table potato (T) and starch potato (PS). The lines in the figure should only be used as a means to identify the different points of the different scenarios and indicates no connection between points in a scenario. Main scenarios, Sc1T and Sc1PS, are highlighted with bold lines, scenarios with susceptible cultivars with solid lines and moderately resistant cultivars with broken lines.

lower doses (75%, 60%, 45% and 30% of recommended) to 98.9%, 98.6%, 97.9% and 96.1% effect, respectively. With long treatment intervals, the effect was worse than with short intervals, although not significant, and 100%, 75%, 60% and 45% of the recommended dose gave 97.3%, 94.3%, 93.3% and 84.8% effect, respectively. In moderately resistant cultivars and at low infection pressure (low PLBMax) in the earlier period, several of the doses applied, whether at short or long intervals, effectively controlled PLB. In susceptible cv. Bintje and at high infection pressure (high PLBMax), the overall effect against PTB was 64% and 59%. In moderately resistant cv. Hertha and cv. Matilda and at low infection pressure (low PLBMax) the overall effect against PTB was 10% and 47%, respectively. In contrast to the treatment effects against PLB, the treatment effects against PTB were not clear and the effects of the treatments seemed random, although in many cases the fungicides appeared to have good activity against PTB.

The average effect against PLB of fungicide treatment at short interval and 100% dose in susceptible Bintje during the recent period 2010-2013 was very high in 2010 (99.5%) but decreased in 2011, 2012 and 2013 to 82.7%, 94.2% and 95.8% effect, respectively. In moderately resistant cultivars such as Ovatio and Sava the effect was very high 2010 ((99.8%) and decreased in 2011 and 2013 to 84.4% and 97.1%,

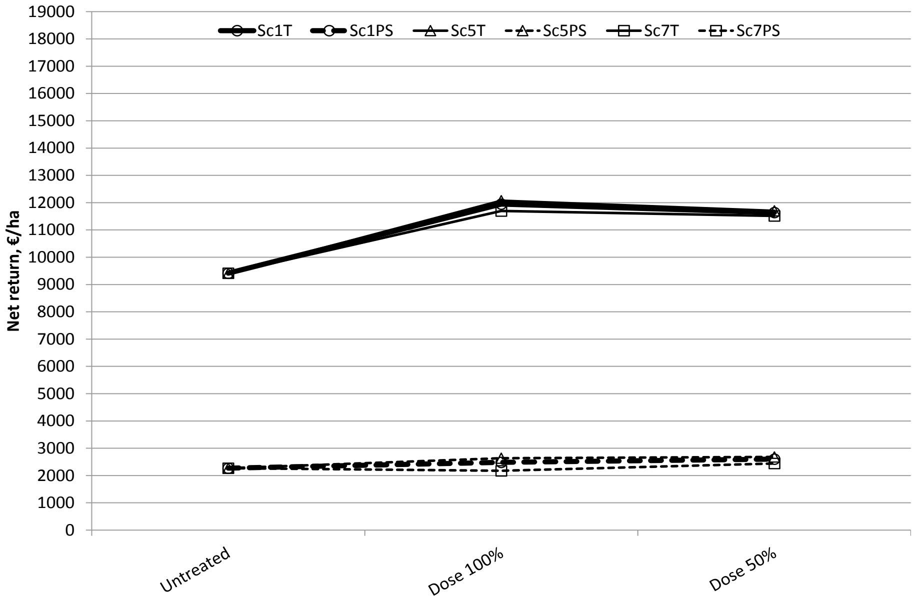

Figure 6: Net return (€ ha^{-1}) 2010-2013 in scenarios with different fungicide prices: Sc1, Sc5, and Sc7 in table potato (T) and starch potato (PS). The lines in the figure should only be used as a means to identify the different points of the different scenarios and indicates no connection between points in a scenario. Main scenarios, Sc1T and Sc1PS, are highlighted with bold lines, scenarios with susceptible cultivars with solid lines and moderately resistant cultivars with broken lines.

respectively, but not in 2012 (99.9%). In starch potato the effect varied depending on year in cultivar Seresta and was 99.2% in 2010, 72.9% in 2011, 41.1% in 2012 and 89.9% in 2013. In the starch potato cultivar Merano with much less severity of PLB, the effect was 99.9% in 2010, 85.6% in 2011, 57.1% in 2012 and 96.9% in 2013.

During the early period the yield increase due to fungicide treatment was relatively low compared with that in the recent period, e.g. the yield increase in susceptible cv. Bintje with short treatment intervals and the recommended dose was on average 9.9 ton ha^{-1} in 1993-1996 and 17.2 ton ha^{-1} in 2010-2013. These changes in effect against PLB and PTB and the yield response due to fungicide treatment are consistent with the quite late occurrence of PBL in Sweden during the early period (1993-1996), on average 88 days after planting, while during the more recent period (2010-2013) PLB occurred on average 63 days after planting, i.e. a difference of almost four weeks (Wiik 2014). As shown many times previously, the resistance of the cultivar against PLB and PTB and the weather conditions in a specific year had a major impact on the strength of the attack.

During the recent period when we calculated RAUDPC, the results showed that with RAUDPC as a measure of PLB, the effect was worse than using PLBMax as a measure. The Pearson correlation (r) between PLBMax and RAUDPC was 0.78***, which shows that the two measures are relatively, although not completely, consistent. This is most likely due to natural wilting having a greater impact in treated plots during the later part of the season, which influences the value of RAUDPC more than the value of PLBMax. Therefore, we used the last secure assessment (PLBMax) before wilting, when it is still possible to make reliable assessments. The effect of fungicides against PLB in recent years has not been 100%, which it was in the past. This agrees well with our observations in the field trials of earlier first attacks and an inability to achieve 100% effect with existing control strategies. This is likely to lead to new control strategies, whereby the first treatment is applied earlier, and an increased interest in forecasting and warning models.

During the two periods described here, 1993-1996 and 2010-2013, conditions differed in several aspects, e.g. agricultural practices including plant protection, biology of *Phytophthora infestans* and weather. During a period covering 1993-1996 only 127 kg nitrogen ha^{-1} were used in the field trials compared to 161 kg nitrogen ha^{-1} during a period covering 2010-2013, something that promotes PLB during the latter period. Use and active ingredients of potato late blight fungicides have changed during the two periods. Broad spectrum and contact fungicides have been replaced by translaminar and systemic fungicides, which among other things, means that the efficacy and life span of certain fungicides are likely to deteriorate more quickly nowadays due to fungicide insensitivity and fungicide resistance. The first attack of late blight occurs earlier since 1998 in Sweden, probably due to a more widespread sexual reproduction leading to a more adaptable *Phytophthora infestans* population that is harder to control [31,37]. During 1993-1996 probably mating types A1 and A2 were not yet fully widespread in Sweden and sexual reproduction in *Phytophthora infestans* occurred to a lesser extent than during 2010-2013. Consequently, late blight was easier to control during the early period. Perhaps the weather due to climate change more than before favors late blight but this needs more investigation. Farmers' profitability in potato farming changes year after year, not least due to supply and demand individual years, and differences follow rather annual trends than trends for two periods, such as 1993-1996 and 2010-2013. Moreover, the economic conditions for individual potato growers have not changed significantly between the two periods.

The recommended dose or treatment interval of a fungicide is normally determined by the company that develops and sells the fungicide. When a product is launched, it sometimes merges that it can be used at lower doses than recommended and still be effective, taking account of the infection pressure and cultivar or host resistance. The total amount of fungicides used over a season can be lowered either by lowering the dose or by lengthening the interval between treatments, but we recommend the former option [30,32,40]. Thus, there are opportunities for potato growers to make cost savings by lowering the total amount of fungicide used. The difference in the doses needed is determined by conditions that can vary. For example, a susceptible cultivar and a high infection pressure require a higher dose than a moderately resistant cultivar and a low infection pressure. A number of studies have also demonstrated that the recommended dose can be reduced, e.g. Olofsson et al. [41] found that it was possible to reduce the dose of EBDC-fungicides (ethylene bisdithiocarbamate, see Gullino et al. [42] such as mancozeb at low infection pressure, in less susceptible cultivars, when treated at short intervals and early in the season when the foliage of the crop was still small. Several studies have investigated the importance of host resistance in relation to the use of fungicides and have concluded that the type of host resistance and fungicides effects are additive [40,43-45]. For example, Andersson et al. [46] used a device for linearly increased injection rate and showed that the effect against PLB was very good with both Tattoo and Shirlan at half the recommended dose. Olofsson and Svensson [47] found that moderately resistant table potato cultivars could use longer treatment intervals, in the cultivar Matilda twice as long as in the susceptible cultivar Bintje. In studies in the UK, it was found that the treatment interval could be extended by up to three weeks with the most resistant cultivars [27]. Moreover, Clayton and Shattock [28] showed that the dose of dithiocarbamate mancozeb could be reduced by 20%-80% for PLB in cultivars with strong non-specific resistance, whereas the full recommended dose was required in a susceptible cultivar. In studies conducted in the early 2000s, Kirk et al. [48,49] in Michigan, USA, showed that it is possible to reduce the dose and extend the range in the treatment of PLB in resistant cultivars. Kapsa [50] found that cultivars with different degree of resistance against PLB require a different amount of fungicide and that this amount is controlled not only by the cultivar but also differences between years, e.g. the infection pressure. The dose in a moderately resistant cultivar could be reduced by 75% at low infection pressure. Using three parameters (AUDPC and PLB severity on two occasions) Kessel et al. [51] demonstrated that the amount of fungicide needed could be estimated based on types of resistance to PLB, and the dose could be reduced by from 46% to at most 81%. In Danish investigations the dose could be reduced by up to 30% if account was taken of the kinds of host resistance and infection pressure (Nielsen et al. 2010). New resistant cultivars, especially with non-specific resistance, can now provide opportunities for forecasting and warning models. Varying the dose with those cultivars is more likely to succeed according to Swedish and Norwegian field trials conducted in the 1990s and 2000s (Wiik 1996, Naerstad et al. 2007). As shown here, both the resistance and tolerance of the cultivar against PLB and PTB and the weather conditions in a specific year have major impact on the severity of attack.

Cultivar Merano was the cultivar that was the most attacked by PTB, with very severe infection in three out of four years during 2010-2013, of the seven potato cultivars included in the present analysis (table potato cultivars Andean Sunrise, Bintje, Ovatio and Sava, and starch potato cultivars Kardal, Seresta and Merano). However, along with potato cultivar Andean Sunrise, Merano had absolutely the best PLB-resistance. The presence of PLB for an extended period in very resistant cultivars, even at low infestation levels, can promote attacks of PTB. One of the conclusions reached by Naerstad et al. (2007) is that the ability to use less fungicide in very resistant cultivars is limited if they lack PTB-resistance. Fungicide untreated cv. Merano used 2011, 2012 and 2013 in our experiments had very high attacks of PTB. However, fungicide treatments with all tested doses were very effective against PTB in comparison with the untreated control 2012 and 2013, but not 2011 when Shirlan was used.

It is worth mentioning that it was not the treatment with the highest yield which gave the best economic net return during the early period (1993-1996). It is also worth mentioning that the net return was significantly higher in susceptible cultivars (Bintje) than in moderately resistant cultivars (Hertha and Matilda), and significantly higher at high infection pressure (PLBMax) than at low infection pressure. Treatment with 60% of the recommended dose and a long treatment interval gave the best net returns during the early period, which is inconsistent with the advice at that time, when full doses were recommended. However, in Denmark during the period before 2006, farmers used 0.2-0.3 l Shirlan ha^{-1} depending on the infection pressure (average dose probably 0.3 l Shirlan ha^{-1}, Bent Nielsen, pers. comm.). Viewed from the perspective of our results, a lower dose than the normally used 0.4 l Shirlan ha^{-1} should also have been recommended in Sweden, at least in the early 1990s.

During the recent period (2010-2013), the susceptible cultivar Bintje required the full dose to give the best net return. Moderately resistant table potato cultivars such as Ovatio and Andean Sunrise gave the best net return at a reduced dose, i.e. 50%-75% of the recommended dose. However, the moderately resistant cv. Sava, which was used in the field trials 2013, gave the best net return at all treatments compared to cv. Bintje. Starch potato cultivars gave the best net returns at low doses, with 25%-50% of the recommended dose being sufficient in many trials. However, in one trial the untreated control gave the best net return, but in another, this was only achieved with the full dose.

The different scenarios tested here are interesting given the customary fluctuations in both potato prices and the costs of production inputs such as fungicides. As expected, higher yield, higher potato prices and lower costs improved the overall profitability for the potato grower. Our calculations showed that, as expected higher yields and higher potato price were crucial to profitability, but also that, using smaller amounts of fungicides led to improved profitability. These results clearly show that it is important to calculate the financial results of field trials. We have previously made financial calculations for crops other than potatoes and the collective results emphasise the importance of such calculations as they can lead to better understanding of the production costs and perhaps to changes in control strategies [33,35,52,53].

The question is whether the results from PLB field trials are sufficiently representative for the use by the advisory services. Interplot interference in field trials has been discussed, e.g. in cultivar trials assessing resistance to PLB and in fungicide trials assessing the efficacy against PLB [54,55]. The number of spores is very high in field trials with untreated plots and untreated spreader rows, challenging both fungicides and cultivars. Therefore, the effect in field trials is probably underestimated [40]. Another obstacle to making accurate decisions based on the results from PLB- and PTB-field trials is that statistically significant differences often exist only between untreated control and treated plots (treatments), at least in Sweden, and not between treatments, e.g. between high and low doses of a PLB-fungicide. However, it would obviously be beneficial to improve the experimental design so that more reliable conclusions can be drawn, e.g. by having greater number of replicates or a different design than the normal randomised complete block approach, supplemented with field trials with linearly increased dosage [46].

In order to reduce the amount of fungicides used in potato cultivation, in our opinion the way forward is to take note of the relatively large number of studies demonstrating that the dose can be reduced without impairing the effect against PLB and PTB and to further investigate the interaction between host plant resistance and fungicide dose.

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