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Economic Impact of Potato Virus Y (PVY) in Europe

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Abstract
As the fourth most prevalent food crop, potato is very important in the global economy, but it is affected by numerous pests, and by many bacterial, viral and fungal diseases. Among these diseases, potato virus Y (PVY), which is transmitted from plant to plant by aphids, causes significant yield losses, but as far as we know, the economic impact of PVY in Europe has not been quantified. Our economic study covers a period of 13 years between 2004 and 2017 and is based on an analysis of statistical, economic and agronomic data, obtained from various stakeholders in the potato sector in Switzerland and the European Union, as well as from field experiments. In Switzerland, the economic loss due to PVY for seed and ware production was estimated at about 2000 and 200 CHF/ha, respectively. For the European Union, the annual losses were estimated at 187 M EUR, respectively 96 and 91 M EUR for seed and ware. These losses were due mainly to the cost of chemical treatments applied in seed potato production and the yield drop in ware potato production. However, based on literature, these significant losses are lower than those caused by potato late blight (*Phytophthora infestans*), which is considered to be the most economically damaging potato disease in Europe.

Keywords Certification · Economy · Loss · PVY · Seed · Ware

Introduction

As the fourth most prevalent food crop, potato is very important in the global economy (FAO 2015), but it is affected by numerous pests, and by many bacterial, viral and fungal diseases. Among these diseases, potato virus Y (PVY), which is

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transmitted from plant to plant by aphids (Fox et al. 2017; Karasev and Gray 2013; Lacomme and Jacquot 2017; Verbeek et al. 2010), causes significant yield loss.

Few studies of the economic impact of potato diseases are available. This is due mainly to limited reliable economic data available at local, national and international levels. Among the available studies, Guenthner et al. (2001) estimated the economic impact of late blight (*Phytophthora infestans*) in the USA at 287.8 M USD (507 USD/ha). Later Haverkort et al. (2008) estimated the economic impact of late blight in the European Union (EU) at 900 M EUR (450 EUR/ha). Recently Dupuis et al. (2021) estimated the economic impact of *Pectobacterium* and *Dickeya*, the pathogens responsible for blackleg and soft rot diseases, on the EU potato production at about 46 M EUR annually.

A study conducted in the USA showed that the yield loss due to PVY was 0.1709 tonnes/ha (Nolte et al. 2004). Moreover, McIntosh (2014) calculated that PVY has a direct impact of 19.56 M USD (about 18.53 M EUR) on the economy of the State of Idaho. Considering that Idaho has 138 K ha of potato, the loss is about 134.64 EUR/ha. The methodology used to obtain the economic data is not described in detail and it is not clear what variables were used in the calculation. Thus overall, there is a need for a systematic analysis of losses due to PVY for all potato sectors covering seed potatoes and ware potatoes (including table potatoes and potatoes for processing). In Switzerland, most of the data for the potato sector are public and relatively easy to access, making a study of the economic impact of PVY possible.

In order to estimate the economic losses due to PVY, we have separated economic losses due to PVY into seven main factors. These are as follows:

$$\text{Total loss} = \text{Ly} + \text{Lt} + \text{Li} + \text{Lr} + \text{Ld} + \text{Lc} + \text{Ln}$$

where Lt, Li, Lr, Ld and Lc are specific to seed potato production (see more details below).

Loss due to Yield Reduction in Seed and Ware Potato Production (Ly)

PVY is responsible for yield reduction in potato crops (Nolte et al. 2004; Whitworth et al. 2010). This yield reduction varies depending on the PVY strain, the potato cultivar, the nitrogen supply and other environmental factors (Whitworth et al. 2010). Limited data are available on the impact of PVY on yield for a large number of potato cultivars. This data is required in order to estimate the average yield loss due to PVY infection caused by the predominant strains, mainly recombinants, which are present in Europe (Dupuis et al. 2019; Glais et al. 2017).

Loss due to Treatments to Control PVY Spread (Lt)

Various PVY control strategies are used in Europe to control PVY spread, of which, mineral oil treatments are the most widely used (Döring et al. 2007; Dupuis et al. 2017a; Rolot et al. 2021; Steinger et al. 2014), although in some countries (e.g. Germany) insecticides may also be used in an attempt to control PVY (Döring et al. 2007). Usually, insecticides are used to control potato leafroll virus (PLRV) spread in seed potato crops (Milosevic 1996; Mowry 2005; van Toor et al. 2009). For PLRV, there is a long acquisition period (several hours) before the immigrating alate aphids become infective, and they are killed before they are able to transmit PLRV. In contrast, the acquisition period for PVY is much shorter (several minutes) and the aphids are usually able to transmit before they are killed (DiFonzo 1996). In ware potato crops, no chemicals are used to control PVY spread since it is considered that primary PVY infections have a low impact on yield (Janssen 2013).

Loss due to Roguing and Field Inspection (Li)

Roguing is the manual removal of potato plants, which are atypical in appearance for the cultivar and those, which have symptoms of virus or bacterial infection (Kerlan et al. 1987). Plant removal is done by the seed potato growers before crop inspection by the official seed certification service, to ensure that the crop meets certification tolerances. These official inspections are usually done several times during the growing season (Dupuis et al. 2017a).

Loss due to the Downgrading and Rejection of Seed Lots (Ld and Lr)

Losses caused by PVY may be due to rejection or downgrading of seed potato lots during certification (Dupuis et al. 2017a). For example, the Swiss regulations for downgrading are that no PVY symptoms are allowed in the field for the initial 3 out of 4 generations of prebasic seed (from class PB1 to PB3), while 0.02% of virus symptoms are allowed for the PB4 class. For the basic seed classes, the same amount of virus is allowed for the S class (0.02%), 0.04% virus for the classes SE1 and SE2, and 0.06% for the E class. Finally, a potato seed lot presenting more than 0.2% of virus symptoms in the field cannot be accepted as certified seed of class A and will be rejected and must be sold as ware (DEFR 2021). At post-harvest testing (qPCR testing in Switzerland), no PVY- and PLRV-infected tubers must be found in the first three generations of prebasic seed (PB1 to PB3), while 0.5% infection is accepted for the classes PB4 and S. For the classes SE1 and SE2, 1.1% of both viruses are accepted, and 2% are allowed for class E. Potato seed lots with more than 10% of tubers infected by PVY and/or PLRV cannot be accepted in the A class, are rejected and must be sold as ware potatoes. These tolerances are similar for other European countries (Dupuis et al. 2017a).

Loss due to the Replacement of Seed Lots (Lc)

The maximum number of field generations is usually nine in European seed potato production systems (Dupuis et al. 2017a). Nevertheless, a seed lot may be rejected before the end of this period for various reasons, such as more than 10% of the tubers being infected by PVY (see above). Therefore, it is assumed that new seed has to be bought to compensate for this loss at a cost proportional to the value of the seed lot that has been lost.

Loss due to Potato Tuber Necrotic Ringspot Disease (PTNRD) on Tubers (Ln)

PVY^{NTN} strain is the causal agent of the potato tuber necrotic ringspot disease (PTNRD) on potato tubers. Infected tubers of susceptible cultivars (e.g. cv. Verdi or cv. Erntestolz) show typical superficial necrotic rings and areas (Tomassoli et al. 1998), which affects the visual appearance of tubers and may lead to rejection of lots of ware potatoes destined for the table market or processing. For each factor described above, a specific methodology was used to calculate the corresponding loss. These methodologies are detailed in "Material and Methods" section. The calculation of the total loss was done for each year starting in 2004 and ending in 2017.

Material and Methods

Loss due to Yield Reduction in Seed and Ware Potato Production (Ly)

To estimate the yield loss in Swiss seed potato production for a given year, the following formula was used:

$$\mathrm{Ly}_{\mathrm{seed}} = \sum\nolimits_{i=PB2}^{A} Q_{1\%} * n_i * s_i * p_i$$

In this equation, the data for each certification class (PB2, PB3, PB4, S, SE1, SE2, E and A) was summed. PB1 is not part of the equation as the potatoes of this class are not produced in open fields and are not exposed to PVY transmission by aphids. "$Q_{1\%}$" is the average yield loss for 1% of PVY for the main cultivated varieties in Switzerland. The "$Q_{1\%}$" was weighted by the % area planted for each cultivar for a given year. To obtain this data for each cultivar, field experiments were performed for 14 years at the Reckenholz station of Agroscope (Canton Zürich, Switzerland), where about 30 cultivars were planted every year with seed of two origins: (i) low altitude (Reckenholz, 440 m asl) and (ii) mountain (Wallestalden, 1011 m asl; Canton Bern). Fifty tubers from each origin were planted side by side with an intra-row spacing of 33 cm and 75 cm between rows. During the growing season, the symptoms of PVY secondary infection were assessed visually and after harvest, the yield was measured. Considering the difference in PVY levels between the two origins, the yield loss for 1% of PVY infection ($Q_{1\%}$) was calculated for each of the 54 cultivars that were tested for at least 3 years. It was obtained by dividing the yield loss for each cultivar by the corresponding increase of PVY percentage, see the equation below for cultivar “X”.

$$Q_{1\%}cv.X = \frac{\left[Yield\ Wallestalden\ seed\ of\ cv.X\ (tons/ha) - Yield\ Reckenholz\ seed\ of\ cv.X\ (tons/ha)\right]}{\left[\%PVY\ Reckenholz\ seed\ of\ cv.X - \%PVY\ Wallestalden\ seed\ of\ cv.X\right]}$$

“n_i” is the average PVY incidence in the “i” certification class. “s_i” is the surface for each certification class planted in Switzerland (in ha), and “p_i” is the average price for each certification class (in CHF).

To estimate the annual yield loss for ware potato production (table market and processing), the following equation was used:

$$\text{Ly}_{\text{ware}} = Q_{1\%} * n_a * s_w * p_w$$

where “n_a” is the average incidence of PVY in A class certified seed the previous year, “s_w” is the area of ware potatoes in Switzerland (ha), and “p_w” is the average price (in CHF) of ware potatoes in the corresponding year.

Loss due to Treatments to Control PVY Spread (Lt)

In Switzerland, the main PVY control method is weekly mineral oil sprays starting at emergence. An estimate was made of these treatment costs per hectare based on Swiss extension literature. We also calculated the cost of insecticide sprays to control PVY as it is a common practice in some European countries such as Germany (Döring et al. 2007).

Loss due to Roguing and Field Inspection (Li)

In Switzerland, all seed potato fields are inspected by official inspectors at least twice a year (DEFR 2021). At first inspection, the inspector determines which fields will need a second “in-depth” visit for counting of PVY diseased plants, to determine whether the crop is within the PVY tolerance for its class. Before this second inspection, the grower is allowed to perform roguing to remove the plants with symptoms. For fields close to a PVY tolerance threshold, additional roguing and additional visits by official inspectors may be needed.

A survey was conducted among key representatives of the seed potato sector to estimate:

- The average price of the field inspection per hectare.
- The average price of roguing per hectare.
- The percentage of crops that are inspected “in-depth” by the official inspectors for counting of PVY diseased plants.
- The percentage of crops for which roguing is performed to remove the plants presenting symptoms.

- For the crops that are inspected "in-depth" for PVY, the number of times these inspections are done per season.
- For the crops for which roguing is performed, the number of times it is done per season.

Loss due to Downgrading of Seed Lots (Ld)

Annual losses due to downgrading at the national level were obtained by calculating the difference between the expected price and the price after downgrading. The following formula was used:

$$Ld = \sum_i (ps_i * q_i) - (pe_i * q_i)$$

where "ps_i" is the price expected for an "i" seed lot (CHF/ton) of the specified certification class (from PB2 to E) and "q_i" is the quantity harvested of the corresponding lot (tonnes). This quantity is calculated by multiplying the seed potato area by the average yield for seed potatoes in Switzerland the corresponding year. "pe_i" is the price of the class finally obtained for the corresponding seed lot after downgrading. *Ld* is the sum of the loss for all downgraded seed lots for a specific year.

Loss due to Rejection of Seed Lots (Lr)

The estimate of the annual losses at the national level due to the rejection of seed lots was obtained for each year by calculating the difference in price between seed and ware potatoes, using the following equation:

$$Lr = \left(p_{seed}{}^{*} q_r\right) - \left(p_{ware}{}^{*} q_r\right)$$

In this equation, "p_{seed}" and "p_{ware}" are respectively the average price of the seed and ware potatoes. The value of "p_{seed}" was weighted by the area planted with each certification class in the corresponding year. "q_r" is the quantity rejected for further seed potato production after official field inspections and post-harvest control tests. The quantity rejected was obtained by multiplying the seed potato area rejected by the average yield of seed potato production in Switzerland in the same year.

Loss due to the Replacement of Seed Lots (Lc)

In Switzerland, if seed lots are rejected for further seed potato production because they exceed 10% virus infection in the tubers, new seed has to be bought to compensate for this loss. We estimate that the total area of potato seed rejected in a given year is replaced by the same surface area planted at a rate of 2 tonnes of seed tubers per hectare. The loss is then the price difference between this seed and the price of the rejected seed sold as ware potatoes.

Loss due to PTNRD (Ln)

Loss due to PTNRD in Seed-Potato Production

Since 2008, external defects have been assessed on 100 tubers of each seed potato lot in Switzerland. Therefore, we have a good estimate of the potato seed lots rejected because of PTNRD symptoms on the tubers. The loss is the difference in price of the seed lot and the price of ware.

Loss due to PTNRD in Ware Potato Production

A survey was done among key representatives of the Swiss potato sector to estimate the percentage of ware potato lots (for the table market and processing) rejected because of the presence of PTNRD symptoms. For these lots, the loss is the difference in the price of the lot and the price of the same quantity of potatoes for livestock feeding.

Comparison with Producer's Gross Margin

By summing losses, we can compare total losses due to PVY with the average gross margin per hectare over the same period (2004 to 2017, available in the annual reports of the Swiss extension services, last reference: AGRIDEA 2017b). This comparison can be made for seed potatoes and ware potatoes for the table market, as well as for potatoes for the processing industry.

Estimation of the Impact of PVY in the European Union

Data for comparison of revenues (income of the crop) and average gross margins (difference between revenues and costs) for table potatoes in six European countries (Czech Republic, Denmark, Italy, Poland, Portugal and Slovakia) in 2002 was obtained from the work of Pedersen et al. (2005). Using this data, economic losses caused by PVY in table potatoes produced in these countries in 2002 were estimated on the basis of the differences in gross margins. These calculations assumed that the losses due to PVY were proportional to the gross margin. The losses were calculated by using the Swiss ratio to gross margin, as described by Dupuis et al. (2021).

The article of Pedersen et al. (2005) included data from countries in most of the main European potato production areas, viz. Northwestern Europe (Denmark), Eastern Europe (Czech Republic, Poland and Slovakia) and Southern Europe (Italy and Portugal). Assuming that the gross margins of these countries are representative of the gross margins of the other countries in the same region, this data can be used to estimate the losses due to PVY for table potato production in the EU.

The average loss per hectare for the table potato sector can be multiplied by the total area of European table potato production in 2002 to obtain the overall loss for this sector (FAOSTAT 2020). Assuming that the ratio of losses by sector in Switzerland is the same as in the EU, we can then also estimate the EU losses in the seed potato sector and the potato processing sector. This assumption is supported by the fact that in all European countries, including Switzerland, the production systems for seed and ware potatoes are very similar, with the same related losses due to PVY. This assumption is discussed further at the end of the article. Finally, to estimate the overall loss for the entire EU potato production, the average loss must be multiplied by the potato area dedicated to the corresponding potato sector in 2002, which is 224,000 ha for seed potatoes, 774,000 ha for table potatoes and 1,337,000 ha for processing potatoes (EUROSTAT 2022; FAOSTAT 2020).

Results

Loss due to Yield Reduction in Seed and Ware Potato Production (Ly)

The percentage of yield loss due to PVY infection for the most cultivated cultivars in Switzerland between 2004 and 2017 is shown in Fig. 1. The average yield loss for these cultivars was 23.5% ranging from 9.6% for cv. Lady Christl to 37.0% for cv. Bintje. From this data, we calculated the average yield loss for 1% PVY infection, as 223 kg/ha.

The average loss for ware potatoes (218.0 CHF/ha) was higher than that for seed potatoes (134.2 CHF/ha) due to the higher prevalence of PVY in ware than

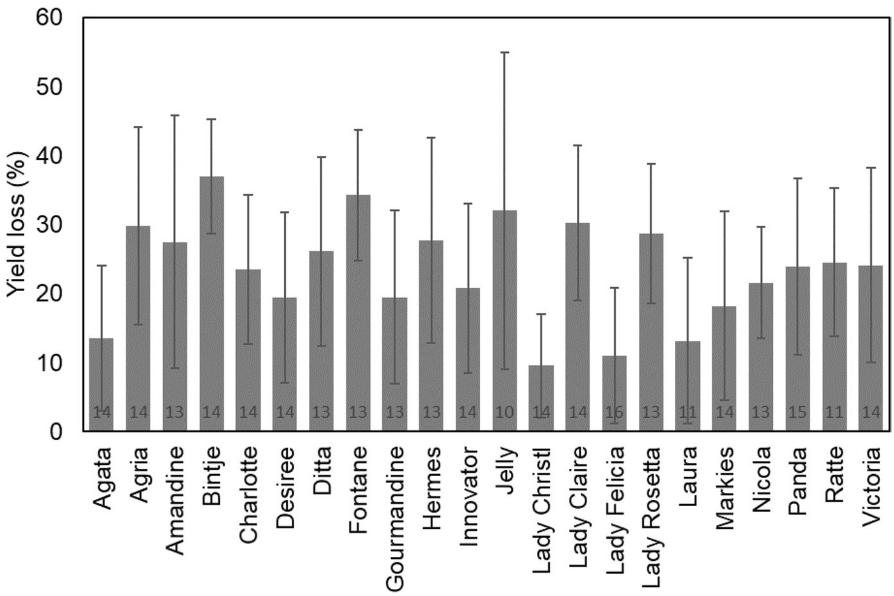


Fig. 1 The percentage average yield loss due to PVY for 22 cultivars tested in the field for at least 10 years. The number shown in the bars is the number of years of trials for the corresponding cultivar. The error shown is the standard deviation

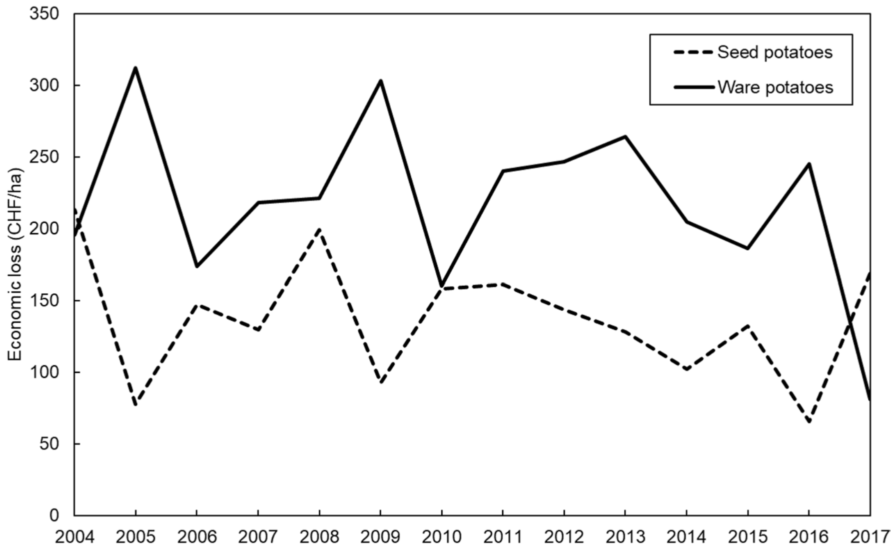


Fig. 2 Economic loss per hectare in Switzerland due to yield reduction caused by PVY of seed and ware potatoes from 2004 to 2017

in seed potatoes (Fig. 2). The average loss for ware potatoes varied from 81 CHF/ha in 2017 to 312 CHF/ha in 2005, while the loss for seed potatoes varied from 66 CHF/ha in 2017 to 213 CHF/ha in 2004.

Loss due to Treatments to Control PVY Spread (Lt)

In Switzerland, it is recommended to spray 7 l/ha of mineral oil to control PVY spread (OFAG 2017), and this recommendation is rigidly followed by seed potato growers from emergence until haulm killing. According to Landi (2017), the product cost for 7 l of mineral oil is 39 CHF. Following AGRIDEA (2017b): the labour cost to treat 1 ha is about 14 CHF; the tractor rental is about 24 CHF/ha, the fuel cost is about 9 CHF/ha and the rental of the sprayer is about 44 CHF/ha. This means that the average cost for one treatment is about 130 CHF/ha. Since seven applications are generally required during the growing season, the total treatment cost is about 910 CHF (827 EUR). For the countries using insecticides to control PVY in the field, the product is usually applied in a mixture with mineral oil. Therefore, the additional cost of using insecticides is only related to the price of the treatment product. For example, a weekly application of lambda cyhalothrin (100 g/l) for 7 weeks represents an additional cost of 105 CHF/ha (95 EUR/ha) to purchase the insecticide (Landi 2017). This additional cost was not used in our calculation as insecticides are usually not recommended to control PVY spread in seed potato fields (DiFonzo 1996).

Loss due to Roguing and Field Inspection (Li)

At the first inspection of the seed crops, the official inspector will decide which crops will need two additional inspections for counting PVY diseased plants. Our survey revealed that 80% of the seed potato crops are subject to these second and third inspections. The other 20% are crops without visible PVY symptoms or those, which have been rejected at the first visit for other reasons. The second inspection is for counting the symptoms of secondary infection, and the third inspection is for counting symptoms of primary infection (Adrian Krähenbühl, SEMAG, Lyssach, Switzerland, personal communication). This inspection costs 50 CHF/ha and as it is done on 80% of the fields twice a year, the average annual cost is 80 CHF/ha.

Our survey also revealed that roguing is usually performed twice a year on 80% of the seed potato fields in Switzerland (Adrian Krähenbühl, SEMAG, Lyssach, Switzerland, personal communication). At an average expense of 300 CHF/ha, roguing represents an average annual cost of about 480 CHF/ha. Since roguing is done to remove plants with disease symptoms, physiological disorders and plants differing from the phenotype, it was not possible to apportion costs solely to removal of PVY-infected plants. Therefore, roguing costs were considered as PVY-related costs.

Loss due to Downgrading of Seed Lots (Ld)

The average loss due to downgrading because of PVY infection was 220.2 CHF/ha, 84.0 CHF/ha lower than the average loss due to rejection of seed lots because

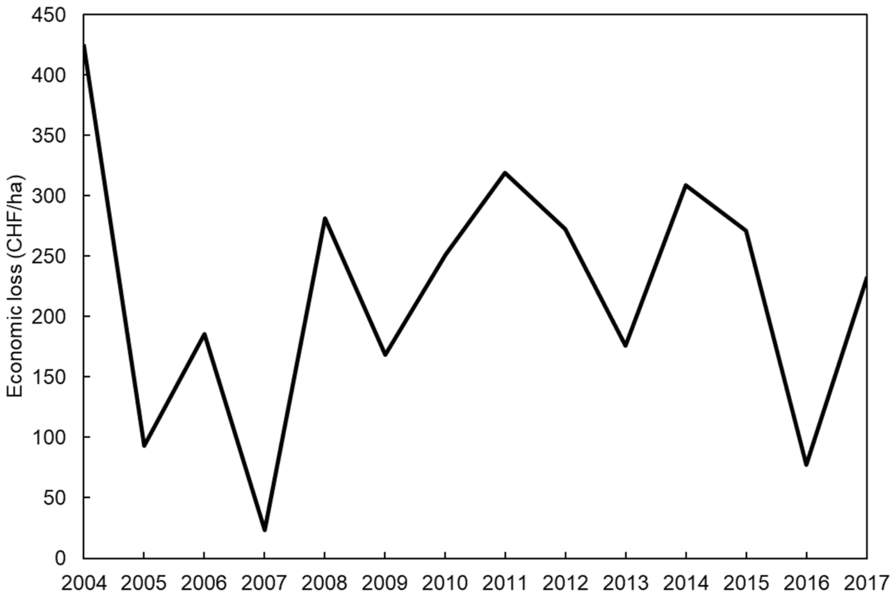


Fig. 3 The economic loss in Switzerland due to downgrading of seed lots due to PVY infection

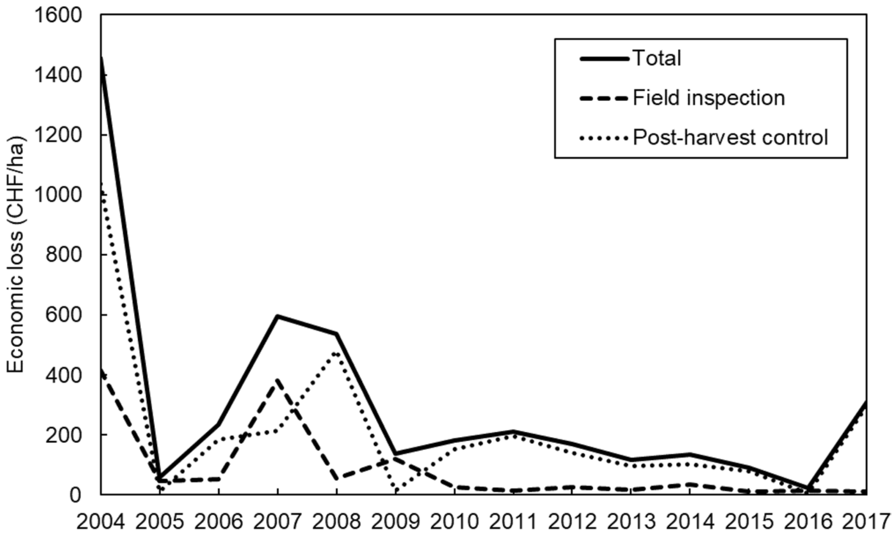


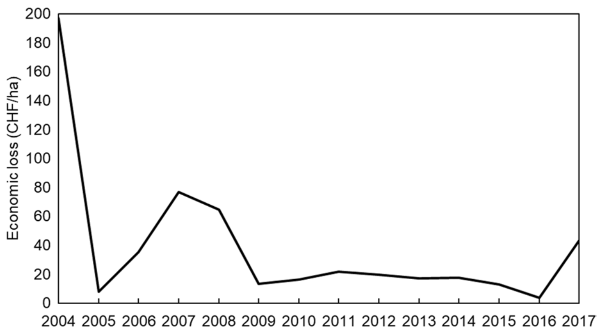
Fig. 4 Economic loss per hectare in Switzerland due to rejection of seed lots because of PVY infection from 2004 to 2017

of PVY infection. The highest loss was observed in 2004 at 424.0 CHF/ha, and the lowest in 2007 at 23.2 CHF/ha (Fig. 3).

Loss due to Rejection of Seed Lots (Lr)

There was a poor correlation between the economic loss at field inspection and the loss after post-harvest control for the same year ($R^2 = 0.4$) for PVY (Fig. 4). This was obvious in 2009 where 121 ha were rejected at field inspection, while only 15 ha were rejected after post-harvest control. The explanation for the poor correlation is that lots rejected at inspection might not be submitted for post-harvest testing, and that there were relatively little late season primary infections. This result shows the benefit of field inspection by rejecting bad seed lots before post-harvest laboratory testing. The average loss due to rejection of seed lots was 304.2 CHF/ha. The

Fig. 5 Economic loss per hectare in Switzerland due to the replacement of seed lots lost because of high PVY infection rates from 2004 to 2017



highest loss due to rejection of seed lots was observed in 2004 at 1454.9 CHF/ha, while the lowest loss was observed in 2016 at 22.4 CHF/ha.

Loss due to the Replacement of Seed Lots (Lc)

The average cost of replacement of rejected seed lots was calculated as on average 39.1 CHF/ha. The highest replacement cost was in 2004 at 197.0 CHF/ha, while the lowest cost was observed in 2016 at 3.7 CHF/ha (Fig. 5).

Loss due to PTNRD (Ln)

Loss due to PTNRD in Seed-Potato Production

After 2008, no PTNRD symptoms were observed in the seed potato samples of 100 tubers taken from each seed potato lot in Switzerland. This suggests that PTNRD did not induce losses in Swiss seed potato production between 2008 and 2017. As the recording of external defects was only initiated in 2008, we have no data for previous years. However, PTNRD symptoms were also probably absent for potato seed lots between 2004 and 2007, as no symptoms were observed during this time by seed certification staff taking sap samples from tubers for PVY testing (Henri Gilliand, Agroscope, Nyon, personal communication).

Loss due to PTNRD in Ware Potato Production (Processing and Table Potatoes)

For processing potato cultivars, PTNRD symptoms are regularly observed on lots of cv. Verdi but rarely observed on lots of cv. Hermes. Nevertheless, in recent years, no potato seed lots have been rejected by industry due to the presence of PTNRD symptoms (Fabien Curty, Zweifel Pomy-Chips AG, Spreitenbach, personal communication). We consider that this was also the case from 2004 to 2017.

Rejection of potato lots dedicated to table potatoes due to the presence of PTNRD symptoms is rare; on average 50 tonnes of potatoes are annually rejected in Switzerland due to PTNRD (Emilien Piot, FENACO cooperative, Bercher, personal

Table 1 Annual estimated losses (CHF/ha) for potato production in Switzerland between 2004 and 2017: for seed potatoes; table potatoes and processing potatoes

Loss factor	Seed potatoes	Table potatoes	Processing potatoes
Yield reduction	137.2 (6.3%)	218.0 (98.7%)	218.0 (100.0%)
Treatments	910.0 (41.9%)	–	–
Roguing and field inspection	560.0 (25.8%)	–	–
Rejection of seed lots	304.2 (14.0%)	–	–
Downgrading of seed lots	220.2 (10.1%)	–	–
Seed replacement	39.1 (1.8%)	–	–
Rejection due to PTNRD	0.0 (0.0%)	2.8 (1.3%)	0.0 (0.0%)
Total	2170.7	220.8	218.0

communication). Considering the difference of price for ware potatoes and potatoes used as animal feed, we estimate the annual loss in Switzerland at 2.8 CHF/ha annually. This loss varies slightly due to the fluctuations in the price of table and animal feed potatoes.

Total Costs in Switzerland and in the European Union

As expected, the highest financial loss is for the seed potato sector with 2170.7 CHF/ha annually (Table 1). This loss is 9.8 times higher than the loss for the table potato sector (220.8 CHF), which is similar to the loss for the processing potato sector (218.0 CHF). The loss for the seed potato sector represents 31.7% of the gross margin/ha for this sector, while it is respectively 3.9% and 3.8% of the gross margin for the table and processing potato sectors (AGRIDEA 2017a). As the EU gross margin for the table potato sector was 1118 EUR/ha in 2002 (Dupuis et al. 2021), we can extrapolate by using the Swiss ratio to gross margin that the loss due to PVY for the corresponding sector would have been 43.6 EUR/ha (3.9% of the gross margin) for the same year. Hence, the loss for the seed potato sector would be 9.8 times higher at 427.3 EUR/ha, and about 43.1 EUR/ha for the processing potato sector (Table 2). Considering the area planted in 2002 for each potato sector (EUROSTAT 2022; FAOSTAT 2020; SEC 2007), we can calculate that the total loss due to PVY in the EU is about 190 M EUR (Table 2). The highest loss is in the seed potato sector with 95.9 M EUR, then the processing potato sector with 57.6 M EUR, and finally the table potato sector with 33.7 M EUR annually.

Discussion

This study shows the high financial cost of PVY for the potato sector in Switzerland and in Europe. In Switzerland, this is highest for the seed potato sector at 2170.7 CHF/ha (1973.4 EUR/ha). It is much lower for table potatoes at 220.8 CHF/ha (200.7 EUR/ha), and for potatoes used for processing at 218 CHF/ha (198.2 EUR/ha). Costs per hectare are probably lower in the EU countries due to the higher price of labour in Switzerland. Nevertheless, by using the ratio of these costs compared to the Swiss gross margin, we could estimate the corresponding costs for the EU as a percentage of the EU potato gross margin. To do so, we used the same methodology as Dupuis et al. (2021) assuming that

Table 2 Average loss per hectare due to PVY for all potato sectors in the European Union (EU) in 2002

Potato sectors	Loss (EUR/ha)	EU surface (K ha)	EU loss (M EUR)
Seed	427.3	224	95.9
Table	43.6	774	33.7
Processing	43.1	1337	57.6
Total	–	2335	187.2

the gross margins of six EU countries are representative of gross margins of the other countries located in the same regions, namely Denmark for Northwestern Europe, Czech Republic, Poland and Slovakia for Eastern Europe, and Italy and Portugal for Southern Europe. This assumption is supported by the similar gross margins of the Eastern Europe countries, ranging from 412 to 623 EUR/ha, compared to the 1537 EUR/ha gross margins for the Danish table potato crops. One could argue that, by considering only Denmark as representative of Northwestern European potato production, we are omitting other major producers such as Belgium, France, Germany, the Netherlands and the UK. However, referring to the recent work of Goffart et al. (2022), who studied potato production in Northwestern Europe over the past 20 years, it is said that the potato economy of Denmark presents the same growth profile as these five countries because of similar economic and production features. For example, the average potato yield was about 47.6 tonnes/ha in Belgium (year 2016), and about 41.1 tonnes/ha in Denmark (average from 2011 to 2016), while the average ex-farm price for potatoes was of 118 EUR/tonne in Belgium and about 99 EUR/tonne in Denmark (Kim et al. 2020). Finally, the gross margins seem to be more different in Southern Europe with 1234 EUR/ha for Italy and 467 EUR/ha for Portugal, but the potato market share of Southern countries is low with only 12.5% of the EU potato area (EUROSTAT 2022).

Using this methodology, we estimated the total loss due to PVY in the EU at about 187.2 M EUR annually. Half of that cost is from the seed potato sector and the other half the ware potato sector (Table 2). The larger area of ware potatoes (9.4-fold more than seed) explains the total loss despite the lower loss per hectare, compared to the seed potato sector. The losses for seed potato production are probably higher in Switzerland compared to the main European potato producing countries, namely Germany, France, the Netherlands, the UK and Belgium (Goffart et al. 2022) because of higher PVY pressure in Switzerland. This higher pressure is due to the continental climate of the Swiss potato production area, which favours aphid flights during the potato growing season (Steinger et al. 2015). This higher pressure results in primary infections that are mainly detected at post-harvest testing. It leads to higher PVY-costs for downgrading, rejection and seed replacement. Nevertheless, these costs only account for 26% of the PVY associated costs for the Swiss seed potato sector (Table 1), and about half of that for the entire potato sector as the seed potato sector is accounting for 51% of all the PVY costs (Table 2). For example, an overestimation of 20% of the downgrading, rejection and seed replacement costs in the EU would result in an increase of only 2.7% of the PVY losses for the entire EU potato sector. Compared to the losses of 900 M EUR caused by late blight (*Phytophthora infestans*) in the EU (Haverkort et al. 2008), the financial impact of PVY is almost 5-fold less for the potato sector. However, we need to treat these results with caution as the methodologies used to calculate the losses due to each pathogen are very different. In addition, the loss calculated by Haverkort et al. (2008) is probably an overestimate as the calculations were based on Dutch data without considering the differences in potato revenue between Western and Eastern countries of the EU. This difference in potato revenues among countries has been taken into account in our calculations as we used a potato gross income for the EU including the differences of potato revenues between western and eastern European countries (see details of calculation in Dupuis et al. (2021)). Nevertheless, it remains that the cost due to late blight is likely to be much higher than that of PVY or any other potato disease, mainly due to the high costs of the fungicide treatments needed to control the pathogen.

Using the same methodology as used for PVY, the economic impact of the bacteria responsible for blackleg and soft rot (*Pectobacterium* spp. and *Dickeya* spp.) (Dupuis et al. 2021) was 4.1 times less than for PVY. This can be explained by two main factors: (i) the occurrence of bacterial outbreaks is much lower than for PVY for which the incidence is high almost every year, and (ii) there is no cost for treatments to control the bacterial diseases, as there is no treatment on the market so far (van der Wolf et al. 2021).

Based on field data, we estimated an average yield loss of 0.223 t/ha for the 22 cultivars most grown in Switzerland between the years 2004 and 2017. This result is consistent with the 0.171 t/ha obtained by Nolte et al. (2004) for the cvs Russet Burbank, Russet Norkotah and Shepody. The PVY cost per ha calculated by McIntosh (2014) of 134.64 EUR/ha is 40% higher compared to our average cost per ha of 80.17 EUR/ha, calculated by dividing the total EU cost of PVY by the total EU potato area. Nevertheless, the difference is not very high and can be explained by three main factors: (i) the difference in potato revenue between Europe and the USA, which was 35% higher in the USA in 2019 (USDA 2020; EUROSTAT 2022), (ii) the differences in methodology used for the two studies, and (iii) the fact that cultivars very susceptible to PVY such as cv. Russet Burbank were very popular in the USA in the early 2000s (Nolte et al. 2004).

In order to reduce the cost impact of PVY, it would be of advantageous to reduce the downgrading and rejection rate of seed potato lots and hence seed replacement losses, which represent 26% of the losses per ha in Switzerland for seed potatoes (Table 1). This can be achieved by using less susceptible cultivars and by implementing new efficient control methods such as the combination of mineral oil spraying and straw mulching (Dupuis et al. 2017b). Another option would be to impose more stringent PVY tolerances for certified seed lots (A class seed). This would reduce the average yield losses due to PVY in the ware potato fields, but would significantly reduce the income of the seed growers. Hence, they would have to be compensated by higher prices for potato seed.

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Declarations

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