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Comparison of Straw Mulch, Insecticides, Mineral Oil, and Birch Extract for Control of Transmission of *Potato virus Y* in Seed Potato Crops

S. M. Kirchner · L. H. Hiltunen · J. Santala · T. F. Döring · J. Ketola · A. Kankaala · E. Virtanen · J. P. T. Valkonen

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Abstract *Potato virus Y* (PVY) is a major pathogen of potato and transmitted non-persistently by aphids. *Aphis fabae* is the main vector of PVY in the High Grade Seed Potato Production Area (HG area) in Finland, where the number of aphids and infection pressure with PVY are rather low, but problems with PVY occur in PVY-susceptible cultivars. The aim of the study was to test straw mulch, mineral oil, birch extract, and insecticides for control of PVY in small-scale field experiments and, additionally, at farm level in growers' fields in the HG area of Finland. The insecticide esfenvalerate reduced the incidence of PVY in the progeny tubers by 29% in one of the 3 years, whereas other chemical treatments or birch extract had no significant effect on PVY incidence. Spraying foliage with mineral oil (Sunoco 11 E/3) reduced the incidence of PVY in 2 years by 43 to 58%, respectively. Straw mulch spread to the field at the time of plant emergence reduced PVY incidence in all 3 years by 50–70%. At farm level, straw mulch reduced the incidence of PVY in the progeny tubers by 25–47%, respectively, in both years tested; however, combining application of straw mulch and mineral oil did not further reduce

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S. M. Kirchner · J. Santala · J. P. T. Valkonen (✉)
Department of Agricultural Sciences, University of Helsinki, P.O. Box 27, 00014 Helsinki, Finland
e-mail: jari.valkonen@helsinki.fi

S. M. Kirchner · L. H. Hiltunen · A. Kankaala · E. Virtanen
Biotechnology and Food Research, MTT Agrifood Research Finland, P.O. Box 413, 90014 Oulu, Finland

T. F. Döring
Department of Agronomy and Crop Science, Humboldt University Berlin, Albrecht-Thaer-Weg 5, 14195 Berlin-Dahlem, Germany

J. Ketola
MTT Agrifood Research Finland, Plant Production Research, 31600 Jokioinen, Finland

incidence of PVY. Successful control of PVY in the HG area of Finland using straw mulch may be explained by transmission of PVY early in the growing season at the time of plant emergence and the relatively low number of vector aphids.

Keywords Aphid · *Potato virus Y* · PVY transmission · Straw mulch · Virus control

Introduction

Potato virus Y (PVY) can cause substantial yield losses in potato, especially as a consequence of secondary infection when PVY-infected seed potatoes are used (Valkonen 2007). Therefore, indexing of PVY is a norm in seed potato certification schemes in many countries (Slack and German 1998; European and Mediterranean Plant Protection Organization (EPPO) 1999; Bolotova et al. 2009; Liu et al. 2011). PVY-resistant cultivars provide the most efficient way to protect potato crops against yield losses caused by PVY, but most cultivars are not resistant to all PVY strains (Tian and Valkonen 2013; Zimnoch-Guzowska et al. 2013). Therefore, it is important to control PVY also by other means, especially when seed potatoes are produced from PVY-susceptible cultivars.

Seed potatoes may be grown in isolation from other potato production to avoid transmission of viruses to seed potato crops by vectors (Wilson and Jones 1990). Seed potato production may also be located in areas where virus transmission is limited due to a low abundance of vectors (De Bokx and Van der Want 1987). When the aforementioned precautionary measures are not sufficient, relatively few options remain available to protect seed potato crops of PVY-susceptible cultivars from infection with PVY (Davidson et al. 2013). PVY is transmitted by winged aphids of many species in a non-persistent manner (De Bokx and Huttinga 1981; Verbeek et al. 2010). This mode of transmission is characterized by brief probing of the plant by the aphid, which is sufficient for acquisition and transmission of the virus (Broadbent and Tinsley 1951; Powell 1991; Martín et al. 1997). Vectors of PVY comprise a wide variety of species, mostly from the family Aphididae, and include potato colonizers and non-colonizers. Species not colonizing potato play a major role in transmission of PVY (Edwards 1963; Bell 1983; Rydén et al. 1983; Harrington et al. 1986; Sigvald 1987; Ragsdale et al. 2001; Kirchner et al. 2011).

The short time sufficient for transmission of PVY, and a dominant role of non-colonizing vectors, renders killing the vector aphids with insecticides inefficient in control of PVY (Radcliffe and Ragsdale 2002). Insecticides fail to kill the vectors fast enough and cause restless behavior of the vectors, which may actually increase transmission of PVY (Broadbent 1957; Perring et al. 1999). Nevertheless, insecticides are often used in attempts to control PVY (Döring et al. 2007), probably because control of PVY is confused with the approaches used to control *Potato leaf roll virus* (PLRV), a persistently transmitted virus. The vectors of PLRV need to settle on potato plants to feed from the phloem for acquiring and transmitting PLRV. Therefore, PLRV can be controlled by killing or reducing aphid populations on potato plants with insecticides (Ragsdale et al. 2001).

Spraying potato foliage with mineral oil can reduce transmission of PVY, as shown by some studies (e.g., Bradley et al. 1962, 1966; Boiteau and Singh 1982a; Kurppa and

Hassi 1989), but contrasting results have also been reported (Radcliffe and Ragsdale 2002; Hansen and Nielsen 2012). The mechanism is not well understood, but mineral oil may affect interactions of virus particles with aphid stylet (Powell 1992) or the behavior of aphids, e.g., by repelling them or delaying sustained feeding behavior (Ameline et al. 2009, 2010).

Another potential method to control the transmission of PVY is mulching the potato field with cereal straw after planting. The efficacy of straw mulching against aphid transmission of viruses has been reported in a wide range of crops, including barley (Kendall et al. 1991), faba bean and rape (Heimbach et al. 2000, 2001, 2002; Saucke et al. 2009), lupins (Jones 1994), vegetables (Summers et al. 2004, 2005), and organically grown potatoes (Saucke and Döring 2004). The mode of action is primarily attributed to the manipulation of the host finding behavior of aphids by the visual properties of straw (Döring et al. 2004). It is also important to note that the efficiency of straw mulch in reducing transmission of PVY depends on vector phenology and appears to be greatest when the vector flight activity peaks early in the growing season (Saucke and Döring 2004). Despite its potential, straw mulch is not widely applied to control PVY and other non-persistently transmitted viruses in seed potato production. One reason may be that there is little information available on how effective straw mulch applications could be when applied at the field scale. Mulching has been tested mainly in small-scale field experiments using high (e.g., artificially augmented) virus inoculum.

European Union (EU) has approved five High Grade Seed Potato Production Areas (HG areas) in which particular measures are taken to ensure freedom from dangerous plant pathogens and pests recognized by EU legislation. The northernmost HG area (latitude 64° N, longitude 25° E) of EU is in Finland where the growing season is short, and the numbers of aphids visiting potato fields are generally low (Kirchner et al. 2011, 2013). In this HG area, the flights of *Aphis fabae* (Scopoli) within a relatively short period of time early in the growing season are responsible for the spread of PVY (Kirchner et al. 2011). The objectives of this study were to test how efficiently mulching with straw can reduce transmission of PVY as compared with application of mineral oil, birch extract, or aphicides in the HG area in Finland. A comparative study to determine the transmission rate of PVY in another region 500 km south from the HG area was carried out in 2009.

Material and Methods

Field Experiments in the HG Area Small-scale field experiments (SSE) were carried out in Lumijoki (64° 49′ N, 25° 16′ E) in 2009, 2010, and 2011 (Table 1). The large-scale experiments (LSE) in farmers' fields were carried out in Tyrnävä (64° 45′ N, 025° 39′ E) in 2011 and 2012 and in Liminka (64° 48′ N, 25° 24′ E) in 2012. The fields were 2–10 m above the sea level at the coastal area of the Gulf of Bothnia (Baltic Sea). The effective sums of temperature during the potato-growing period (weeks 25–36) were 835, 852, 908, and 791 °C in 2009, 2010, 2011, and 2012, respectively, and precipitation was 166, 186, 278, and 195 mm, respectively. The soil was fine sand and pH varied from 5.5 to 5.8. The Biologische Bundesanstalt, Bundessortenamt and Chemical industry (BBCH) phenological growth stage system (Hack et al. 1993) was used to assess the growth stage of potato plants weekly during the growing season.

Table 1 Details of the field experiments and their management

	Small-scale experiments (SSE)			Large-scale experiments (LSE)		
	2009	2010	2011	2011	2012	2012
Experiment code	SSE09	SSE10	SSE11	LSE11	LSE12a	LSE12b
Potato cultivar	Asterix	Asterix	Asterix	Velox	Tanu	Van Gogh
PVY (%) in seed tubers	4.0	3.5	4.7	0.3	0.7	3.5
Planting date	2 June	27 May	30 May	20 May	4 June	4 June
Date of 50% emergence (BBCH 09)	24 June	22 June	21 June	21 June	28 June	3 July
Date of complete crop cover (BBCH 40)	18 July	13 July	8 July	6 July	18 July	18 July
Harvest date	1 September	7 September	7 September	9–10 September	11 September	30 August
No. of treatments	6	6	3	1	1	2
No. leaves tested for PVY per treatment	700	700	1,000	600	600	600
No. of progeny tubers tested for PVY per treatment	120	100	180	1,000	1,000	600
Haulm killing (mechanical/chemical)	18.8/18.8	24.8/26.8	23.8/24.8	10.8/12.8	−/27.9	−/24.8
Fertilizer[a]	545 kg/ha (N11:P5:K18)	750 kg/ha (N8:P5:K19)	750 kg/ha (N8:P5:K19)	600 kg/ha (N6:P5:K20)	650 kg/ha (N8:P5:K19)	700 kg/ha (N6:P5:K20)
Herbicide application[b]	1 (19.6.); 2 (25.6.)	3 (22.6.); 4 (9.7.)	3 (23.6.)	5 (16.6.)	6 (25.6.)	7 (24.6.)
Late blight control scheme[c]	1,1,2,3,3,3	4,4,2,2,5,5,5	1,1,6,3,3,3,3,	3,2,2	1,1,3,5,5	2,2,3

[a] YaraMila Puutarhan Y 1-3 (Yara Suomi Oy, Espoo, Finland)

[b] The herbicides used are as follows: (1) Titus 30 g/ha [active ingredient (a.i.): rimsulfuron 250 g/kg] (Berner Oy, Helsinki, Finland) + Senkor 140 g/ha (a.i. metribuzin 700 g/kg) (Bayer Crop Science, Espoo, Finland) + Sito Plus 2 dl/ha (a.i. alcohol ethoxylate 90%) (Berner Oy, Helsinki, Finland); (2) Titus 20 g/ha + Sito Plus 2 dl/ha; (3) Titus 30 g/ha + Senkor 150 g/ha + Sito Plus 2 dl/ha; (4) Titus 30 g/ha + Sito Plus 2 dl/ha; (5) Senkor 400 g/ha + Sito Plus 2 dl/ha; (6) Afalon 2 l/ha (a.i. linuron 450 g/l) (Hankkija-Maatalous Oy, Hyvinkää, Finland); (7) Titus 20 g/ha + Senkor 200 g/ha + Sito Plus 2 dl/ha

[c] The fungicides used are as follows: (1) Tyfon 2 l/ha (a.i. fenamidone 75 g/l and propamocarb 375 g/l) (Bayer Crop Science, Espoo, Finland); (2) Revus 0.6 l/ha (a.i. mandipropamid 23.3%) (Syngenta Crop Protection A/S, 21110 Naantali, Finland); (3) Shirlan 0.4 l/ha (a.i. fluazinam 38.8%) (Syngenta Crop Protection A/S, 21110 Naantali, Finland); (4) Acrobat 2 kg/ha (a.i. mancozeb 60% and dimethomorph 9%) (BASF Oy, Helsinki, Finland); (5) Ranman A 0.2 l (a.i. syatsofamidi 23%) + Ranman B 0.15 l (a.i. polyalkyleneoxide modified heptamethyltrisiloxane 36%) (Berner Oy, Helsinki, Finland); and (6) Tanos 0.7 kg/ha (a.i. famoxadone 250 g/kg and cymoxanil 250 g/kg) (DuPont Suomi Oy, Kantvik, Finland)

SSE The SSEs (Fig. 1a) compared insecticides, mineral oil, birch extract, and the use of straw mulch in control of PVY. Procedures were based on EPPO guidelines for efficacy evaluation of insecticides (EPPO 2008). Barley straw was applied by hand at 5.5 t/ha when potatoes were about to emerge in June (Table 2). Insecticide treatments included foliar sprays with (i) esfenvalerate at 15 g/ha, (ii) combination of tau-fluvalinate at 60 g/ha and thiacloprid at 60 g/ha, and (iii) tuber dressing with thiamethoxam at 4.9 g/100 kg of seed potatoes. Mineral oil (Sunoco 11 E/3, Berner, Helsinki, Finland) was used as a 1.5% solution in water. Birch extract (Charcoal Finland Ltd, Alavieska, Finland) shown

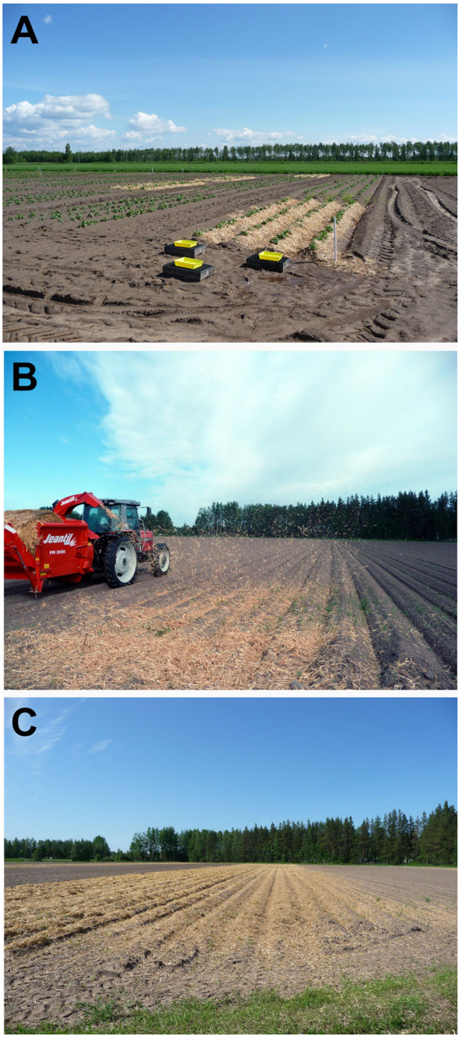

Fig. 1 Design of small-scale experiments (SSE) and large-scale experiment (LSE). **a** Randomly distributed experimental plots to test treatments with straw mulch, mineral oil, birch extract, and aphicides (June 28, 2011). Yellow pan traps were used to monitor aphids from planting to harvest of potatoes. **b** Bale chopper (Jeantil PR 2000) used for straw mulch application in LSEs (June 17, 2011). **c** A sector of a farmer's field covered with straw and separated from the other sector covered with straw (*to the left*) with a sector containing no straw in an LSE (June 17, 2011)

to repel molluscs (Lindqvist et al. 2010) was applied as 1.5% solution in the SSE of 2009 (SSE09) or 3% solution in water in the SSE of 2010 (SSE10) (Table 2). The first foliar spray with insecticides, mineral oil, or birch extract was applied when 50% of the plants had emerged. Treatments were repeated weekly until flowering of plants (BBCH 60). In the SSE of 2011 (SSE11), the treatments with birch extract, thiamethoxam, and the combination of tau-fluvalinate and thiacloprid were not included.

Experiments were arranged according to the completely randomized block design with four replications. Plot size was 8.0 m×3.2 m (four rows). The plots were separated from each other by bare soil strips of 2.5 m. The experimental area was surrounded by an oat crop at a 5-m distance from potato plots. The seed potatoes (cultivar Asterix) used for planting were infected with a strain of PVY^{NTN} (Tian et al. 2010). All plots of an experiment were planted with tubers from the same PVY-infected seed lot. Infection rate in the seed lots was 3.5–4.7%, as determined by sampling leaves from 700 to 1,000 plants of the experiment 2 weeks after emergence. Leaf samples were tested for PVY by double antibody sandwich ELISA (DAS-ELISA) (Table 1) using polyclonal antibodies and alkaline phosphate-conjugated polyclonal antibodies detecting all strains of PVY (Adgen Phytodiagnostics, Neogen Europe Ltd., Ayr, UK), as described (Kirchner et al. 2011). Planting distance was 0.28 m within a row and 0.8 m between rows. The experimental areas were fertilized with 60 kg/ha of nitrogen (Table 1). Weeds were controlled with one (SSE11) or two (SSE09 and SSE10) herbicide applications (Table 1) before straw mulch was spread. Late blight was controlled with six (SSE09) or seven (SSE10 and SSE11) applications (Table 1).

A total of 50–52 plants from the two middle rows of each plot were harvested 92, 103, and 100 days after planting in SSE09, SSE10, and SSE11, respectively (Table 1), graded for size and weighed. A total of 120, 100, and 180 progeny tubers from experiments SSE09, SSE10, and SSE11, respectively (30, 25, and 45 tubers per plot, respectively) were sprouted and the young leaves tested for PVY using DAS-ELISA, as described (Kirchner et al. 2011).

Table 2 Treatments and numbers of applications tested for control of transmission of PVY

	Barley straw	Sunoco 11	Esfenvalerate	Tau-fluvalinate and thiacloprid	Thiamethoxam	Birch extract
Application rate	5.5 t/ha	12 l/ha[a]	15 g/ha	60 g/ha	4.9 g/100 kg seed potatoes	12 l/ha (2009) 24 l/ha (2010)[b]
Number of applications						
SSE09	1	5	4	3× tau, 1× thi[c]	1	5
SSE10	1	5	3	2× tau, 1× thi[c]	1	5
SSE11	1	4	3	0	0	0

Only one type of treatment was applied to each experimental plot, except in LSE12b in which the same plot was treated with straw mulch and Sunoco 11

[a] 1.5% solution in water

[b] 1.5% water solution in 2009 and 3% water solution in 2010

[c] Treatments with tau-fluvalinate (tau) and thiacloprid (thi): in SSE09 tau-fluvalinate 2.7, 9.7, and 16.7 and thiacloprid 24.7; in SSE10, tau-fluvalinate 6.7 and 15.7, and thiacloprid 22.7

LSE LSEs were set up in grower's seed potato fields, i.e., in one field in 2011 (LSE11) and two fields in 2012 (LSE12a and LSE12b). Incidence of PVY in the seed potato lots used for planting was 0.3% in LSE11 (cultivar Velox), 0.7% in LSE12a (cultivar Tanu), and 3.5% in LSE12b (cultivar Van Gogh) (Table 1). Sizes of the fields were 2.1 ha (LSE11), 2.0 ha (LSE12a), and 6.5 ha (LSE12b). Straw was spread to two sectors (width 16 m) of the field and separated and bordered by sectors of similar width but without straw (Fig. 1c). Lengths of the sectors were 120 m (LSE11), 115 m (LSE12a), and 150 m (LSE12b). The two mulched and two non-mulched sectors were divided into two parts in order to have four replications per treatment. Barley straw was applied with a bale chopper (Jeantil PR 2000, L'Hermitage, France) at 5 t/ha when plants were emerging (Fig. 1b).

In LSE12b, a combination of straw mulch and mineral oil treatment was used. Mineral oil was applied as a 1.5% suspension in water. The mineral oil was first applied at plant emergence. Four additional applications were done at 1-week intervals until flowering (BBCH 60) (application dates July 9, 17, 24, and 30 and August 6).

The trials were managed by the grower in accordance with seed potato production practices typical to the region (Table 1).

An area (12 m×4.8 m) including 262–300 plants was marked in the center of each replication and the incidence of PVY determined by testing leaves from 125 plants 2 weeks after emergence. The average yield was determined by harvesting and weighing the crop from the area of 6 m^2 in each sampling area, and 125–250 tubers from the yield were tested for PVY.

Estimation of Vector Pressure Monitoring of aphids was started in the middle of June before potato plants emerged and continued until harvest in the beginning of September. The standard yellow pan traps (YPTs) (Syngenta Agro GmbH, Maintal, Germany) used were 27.0×33.0×8.0 cm (width×length×height) in size. They were filled with ca. 1.5 l of tap water containing 1 ml of 50% Tween 20 as an odorless detergent and placed at the edge of the field. The traps were emptied twice a week and the catch was stored in 70% ethanol. All aphids were identified as described (Kirchner et al. 2011, 2013). Vector pressure was estimated based on the aphids caught during the period of time from plant emergence (BBCH 09) to closure of canopy (BBCH 40). The numbers of nine aphid species known to be efficient vectors of PVY were considered, and their species-specific relative efficiency factors as vectors of PVY according to van Hoof (1980) were used because they were experimentally found to be best fitting in the HG area of Finland (Kirchner et al. 2011). The resulting values over the nine species were calculated for each experiment to obtain the estimate of vector pressure, as described (Kirchner et al. 2011).

Statistical Analysis Generalized linear models (GLM) were used to determine differences between treatments with blocks as fixed effects. Multiple comparisons of means with the untreated control were performed with the Dunnett test. Grubbs test (Grubbs 1969) identified one outlier in the control of SSE10, which was removed from the analysis. The incidence of PVY in the LSEs was compared with the incidence of PVY predicted by the epidemiological model of PVY transmission in the HG area (Kirchner et al. 2011). For the prediction of the incidence of PVY, multi-model inference (MMI) estimates were used for vector pressure, virus resistance, and incidence of PVY in the seed tubers. All analyses were done using "stats," "multcomp," and "outlier" packages in R, version 2.12.1 (Crawley 2007; R Development Core Team 2011).

Field Trial for Testing Transmission Rate of PVY in a Southern Region of Finland Besides the HG area (Kirchner et al. 2011), which is located at the northernmost potato-growing area of Finland, the rate of PVY transmission in potato crops has been studied in only few other regions of the country (Tiilikkala 1987). Therefore, a trial was carried out in the experimental farm of University of Helsinki in Viikki, Helsinki (60° 14′ N, 25° 02′ E), in 2009. The field was 2 m above the sea level at the coast of Gulf of Finland (Baltic Sea). The only aim of this experiment was to determine the rate of PVY transmission.

The experimental plot was placed in the middle of a wheat field. Plot size was 12.6 m×12.6 m. Distance between rows was 70 cm. Seed potatoes were planted at a distance of 28 cm. The experimental plot was bordered with a 5-m wide zone of bare soil (Online Resource 1).

Aphids were caught using four yellow traps each placed at a different edge of the experimental plot. PVY vector pressure was determined as explained above.

The highest class of certified seed potatoes of cultivar Asterix (max. 2% infected with PVY) was used to plant the experiment. Planting was done on May 25. Two weeks after emergence, leaves were sampled from all 792 plants. Plants were numbered and leaves from ten plants were pooled for testing for PVY by DAS-ELISA, as described above. Fifteen pools were found to be PVY-positive. All samples of these pools were tested separately to identify the PVY-infected plants, which were subsequently removed from the field.

Infector plants for the experiment were obtained from a tuber lot of cultivar Asterix highly infected with PVY^{NTN} (Tian et al. 2010). Tubers were sprouted and young leaves tested by DAS-ELISA with PVY strain group-specific monoclonal antibodies obtained from Science and Advice for Scottish Agriculture (SASA, Edinburgh, Scotland). The infector tubers positive for PVY^{NTN} were used to replace 36 healthy seed tubers, so that the infectors were distributed evenly over the whole plot (Online Resource 1) and a seedborne PVY infection rate of 4.5% was achieved.

Potatoes were harvested at the end of August. Tubers from each infector plant and each of the eight plants surrounding the infector plant were collected separately. Tubers from the remaining plants were combined in one lot. Tubers were stored at +8 °C for 7 months, sprouted, and tested for PVY by DAS-ELISA. Three tubers of each infector plant and each surrounding plant were tested by sampling leaves from two stems of the plant. The incidence of PVY in the tubers of remaining plants stored as one lot was tested by taking three samples of 50 tubers from the lot and testing the tubers as described above.

Results

Vector Pressure In the SSEs, vector pressure during the 3-week-long period from emergence of plants (BBCH 9) to the closure of canopy (BBCH 40) was at similar, relatively low levels in all 3 years (Table 3). In the LSEs, the vector pressure was generally higher than in the SSEs. The highest vector pressure was observed in LSE12b. In the SSEs and LSEs, *A. fabae* was the most abundant aphid species known for its high capacity to transmit PVY (Table 3).

SSE In the SSEs, the incidence of PVY in the seed tuber lots was 4.0, 3.5, and 4.7%, in 2009, 2010, and 2011, respectively, whereas PVY incidence in the yield was 38, 36, and 52%, respectively, in the control plots. Vector pressure was 16.8, 12.6, and 20.1, respectively (Table 3). In contrast, the application of straw mulch limited the spread of PVY significantly as compared with controls, resulting in lower PVY incidence of 12% ($p<0.001$), 18% ($p<0.05$), and 26% ($p<0.001$) in 2009, 2010, and 2011, respectively (Fig. 2). Furthermore, the incidence of PVY was significantly lower in plots treated with Sunoco 11 E/3 than in control plots in 2009 (22%, $p<0.05$) and 2010 (15%, $p<0.001$). In plots treated with esfenvalerate, the incidence of PVY was lower than in control plots only in 2011 (29%, $p<0.05$) (Fig. 2c). Other treatments did not significantly reduce or increase the incidence of PVY as compared with the untreated controls.

Treatments used to control PVY did not influence the yield significantly. In average, yield was 34 t/ha in all treatments and years. No differences among blocks were observed for all years. In 2010, one replication of the untreated control with 4% PVY in the harvested tubers was removed from the dataset.

LSE In LSEs, the incidence of PVY in the seed lots was 0.3% (LSE11), 0.7% (LSE12a), and 3.5% (LSE12b), whereas PVY incidence in the yield was 4.4, 0.6, and 27%, respectively, when no control measures against transmission of PVY were used. Vector pressure was 22.4, 108.5, and 471.8, respectively (Table 3). The incidence of PVY was significantly lower in the field sectors mulched with straw in LSE11

Table 3 The PVY vector pressure in 2009–2012, the incidence of PVY in the seed potato lots used to plant the experiments, and the incidence of PVY in the yield harvested from control plots. Vector pressure calculations were based on relative efficiency factors (REF) (van Hoof 1980) of aphids caught with yellow pan traps between emergence and canopy closure (BBCH 09-40)

Species	REF	No. of aphids						
		SSE09	SSE10	SSE11	LSE11	LSE12a	LSE12b	SF
Acyrthosiphon pisum	0.28	2	13	0	2	0	3	2
Aphis fabae	0.48	28	15	30	35	188	976	50
Aphis pomi	0.18	0	0	1	1	0	0	0
Aulacorthum solani	0.10	6	2	4	15	28	9	0
Capitophorus hippohaes	0.06	1	3	4	2	56	0	0
Macrosiphum euphorbiae	0.58	2	2	3	5	19	0	0
Metopolophium dirhodum	0.06	12	0	17	2	14	11	2
Myzus persicae	1.00	0	0	1	0	0	0	0
Rhopalosiphum padi	0.04	7	5	27	6	6	23	21
Total vector pressure		16.8	12.6	20.1	22.4	108.5	471.8	25.52
PVY-% in seed potatoes		4.0	3.5	4.7	0.3	0.7	3.5	4.5
PVY-% in yield		38	36	52	4.4	0.6	27	67
Increase of PVY (fold)		9.5	10.3	11.1	14.6	0.9	7.7	14.9

SSE small-scale experiment, *LSE* large-scale experiment, *SF* Southern Finland. See Table 1 for coding

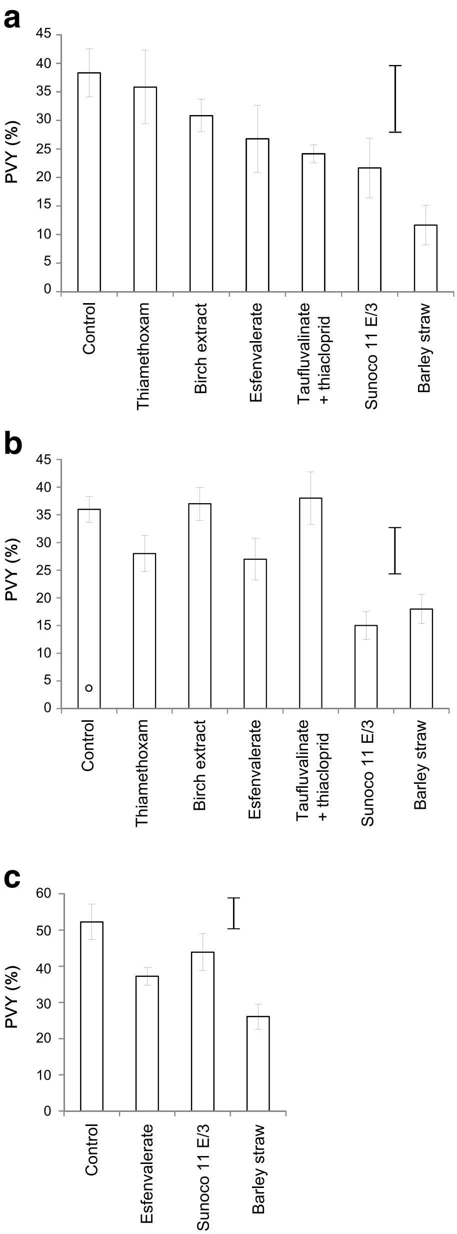

Fig. 2 Incidence of *Potato virus Y* in the progeny tubers in the small-scale experiments (SSE) in **a** 2009, **b** 2010, and **c** 2011. Standard error of a difference between means (SED) is indicated with *bars* (**a**, SED=11.9; **b**, SED=8.7; **c**, SED=8.2). Significant contrasts of treatments compared with control identified by Dunnett's test: **a** straw mulch (p<0.001; df=18); Sunoco 11 E/3 (p<0.05; df=18); **b** straw mulch (p<0.05; df=17); Sunoco 11 E/3 (p<0.001; df=17); **c** straw mulch (p<0.001; df=9); Esfenvalerate (p<0.05; df=9). For the numbers of tubers tested, see Table 1. PVY-% in seed potatoes: **a** 4.0, **b** 3.5, and **c** 4.7

(2.3%, p<0.05) (Fig. 3a) and LSE12b (20%, p<0.01) (Fig. 3c) than in untreated sectors. Combined application of straw mulch and mineral oil in LSE12b also resulted

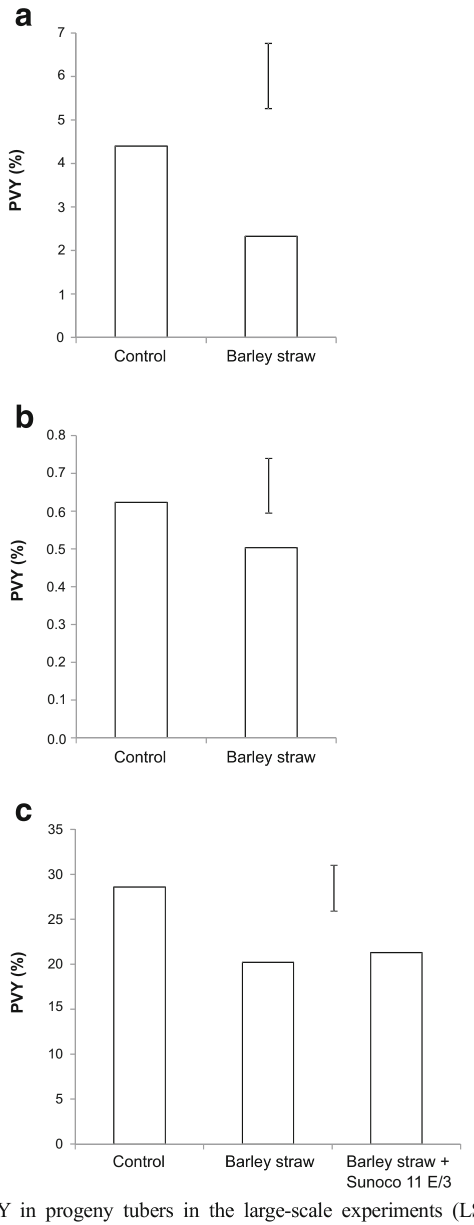

Fig. 3 Incidence of PVY in progeny tubers in the large-scale experiments (LSE). Standard error of a difference between means (SED) is indicated with *bars*. **a** LSE11 (SED=1.5). **b** LSE12a (SED=0.15). **c** LSE12b (SED=5.1). Significant contrasts of treatments compared with control identified by Dunnett's test: **a** straw mulch ($p<0.05$; $df=6$). **c** straw mulch ($p<0.01$; $df=9$; straw mulch + Sunoco 11 E/3 ($p<0.01$; $df=9$). For the numbers of tubers tested, see Table 1. PVY-% in seed potatoes **a** 0.3, **b** 0.7, and **c** 3.5

in lower incidence of PVY in the yield (22%, $p<0.01$) than in untreated controls (Fig. 3c).

LSE12a was carried out in a field different from LSE12b, and little spread of PVY was observed regardless of the considerable vector pressure (Table 3), as indicated by no actual difference in the incidence of infection in the tuber yield (0.6%) as compared with the seed potatoes planted (0.7%) (Table 3). In the field sectors of LSE12a covered with straw mulch, the incidence of PVY in the yield was 0.5% (Fig. 3b). It seems that the cultivar (Tanu) used in this experiment may express field resistance against transmission of PVY, which needs to be studied in more detail.

Yield was not affected by any treatment in the LSEs (Fig. 4).

Transmission of PVY in Southern Finland Testing three tubers per plant for PVY showed that 76% of the plants growing next to a PVY^{NTN}-infected plant got infected with PVY during the growing season. The tubers of the remaining plants were combined to one lot, and three samples of 50 tubers from the lot were tested for PVY as described above. Incidence of infection in the tuber yield harvested from the plants not growing next to the infector plants was 67% (Online Resource 1). Hence, the incidence of PVY in the yield was slightly higher in southern Finland (67%) than in the SSEs in the HG area (38–52%), although the incidence of PVY in seed potatoes planted was similar (4.5 vs. 3.5–4.7%, respectively). These results were consistent with a slightly higher vector pressure in the field in southern Finland (25.5), as compared with the SSEs in the HG area (12.6–20.1) (Table 3).

Predicted and Measured Incidence of PVY in LSE11 and LSE12 In LSE11, the measured and predicted incidence of PVY was 4.4 and 2.0%, respectively (Fig. 5). In LSE12a, the measured and predicted incidence of PVY was 0.6 and 3.5%, respectively, and in LSE12b, it was 27 and 19%, respectively (Fig. 5).

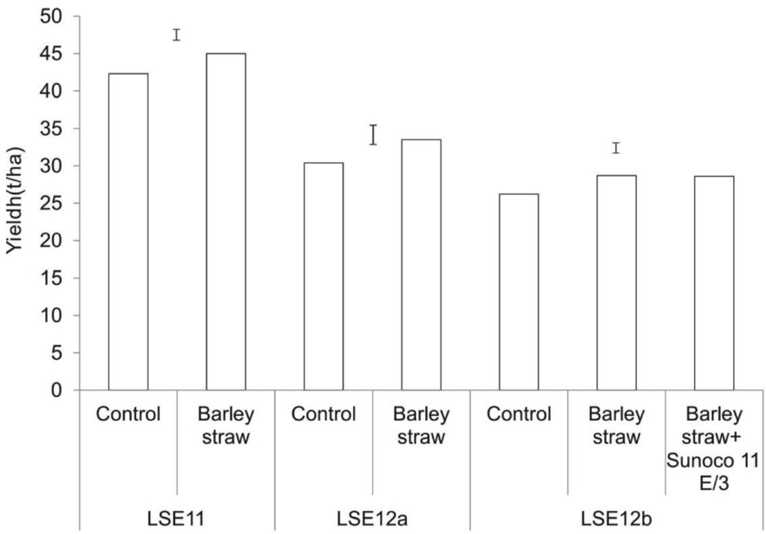

Fig. 4 Mean tuber yields (n=4) per treatment in the large-scale experiments (LSE11, LSE12a, and LSE12b). Standard error of a difference between means (SED) is indicated with *bars*. LSE11, SED=1.5; LSE12a, SED=2.6; LSE12b, SED=1.4

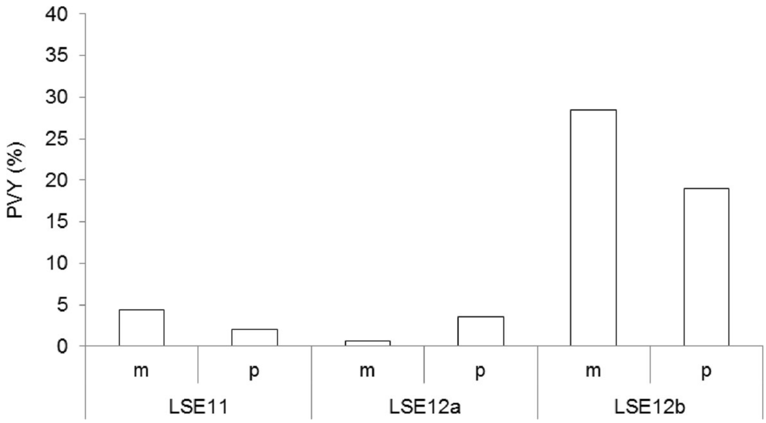

Fig. 5 Predicted and measured incidence of PVY in the large-scale experiments (LSE11, LSE12a, and LSE12b). *m*, measured incidence of PVY; *p*, predicted incidence of PVY

Discussion

The results of this study indicate that straw mulch can reduce PVY transmission consistently over years, fields and potato cultivars, resulting in 50–70% lower incidence of PVY in the yield as compared with untreated crops. It is likely that straw mulch decreases PVY incidence by reducing landing of aphids on the plants, which in turn is caused by fading contrast of plants against the background in lack of bare soil (Döring et al. 2004). Therefore, straw mulch is effective in the growth period from emergence of the plants until closure of canopy (Gibson and Rice 1989; Heimbach et al. 2002; Saucke and Döring 2004). The success in controlling PVY with the use of straw mulch in this study is consistent with the previous studies showing that transmission of PVY in the HG area of Finland occurs during the first 2 or 3 weeks after emergence of potato plants (Kirchner et al. 2011).

Few or possibly no previous studies have compared straw mulch with other treatments, such as application of mineral oil or insecticides, in the control PVY transmission in potato crops. Our studies showed that spraying foliage of potato crops with mineral oil reduced the incidence of PVY less reliably than the use of straw mulch. In the yield of the mineral oil-treated crops, the incidence of PVY was reduced in 2009 and 2010, in contrast to 2011. The vector pressure was similar in 2010 and 2011; however, one mineral oil treatment was omitted in 2011, as compared with other years. Furthermore, precipitation in 2011 was higher than in the previous years, which may have caused a higher loss of oil and reduced protection (Boiteau and Wood 1982). These factors may explain the differences in protection from PVY provided by mineral oil treatments in different years. There are previous studies showing that treatment of potato foliage with mineral oil alone (Bradley et al. 1966; Boiteau and Singh 1982b; Tiilikkala 1987; Wróbel 2012) or with insecticides (Gibson and Rice 1986; Bell 1989; Boiteau et al. 2009) reduces the incidence of PVY; however, whether insecticides contribute to control of PVY when applied in combination with mineral oil is doubtful, as indicated by our study and previous studies (Tiilikkala 1987; Radcliffe and Ragsdale 2002; Hansen and Nielsen 2012). As in our study, application of mineral oil is not always effective in control of PVY (Shands 1977; Hansen and Nielsen 2012) and may cause foliar symptoms and yield reduction in sensitive potato cultivars (Kurppa and Hassi 1989).

In Finland, spraying with insecticides such as deltametrin has not protected potato crops against PVY in previous studies (Tiilikkala 1987), consistent with our study which tested other insecticides. Negative results from application of insecticides against transmission of PVY in potato crops are reported frequently (Döring et al. 2007), but some control may be achieved by reducing aphid populations in crops that are colonized by aphids (Sigvald 1987; Radcliffe and Ragsdale 2002). Few if any aphids are known to colonize potato plants in Finland (Kurppa and Rajala 1986; Tiilikkala 1987; Kirchner et al. 2011). Application of insecticides also imposes risks, such as development of insecticide-resistant pest populations (Devonshire 1989; Rongai et al. 1998; Robert et al. 2000), environmental hazards (Pretty et al. 2000), negative impacts on beneficial organisms (von der Ohe et al. 2004), and risks to human health including the farmers and consumers. Hence, there are many reasons not to use insecticides for the control of PVY in potato crops. Birch extracts have been used successfully for repelling snails (Lindqvist et al. 2010), but in our study, it was not efficient against aphids transmitting PVY.

Additional benefits from straw mulch, besides reduction of the spread of PVY, were the consistently observed tendencies towards increased yield and reduced incidence of common scab, both of which may be associated with better maintenance of soil moisture (Greb 1966; Unger 1978; Bhatt and Khera 2006). Straw mulch can help to decrease soil erosion (Döring et al. 2005; Bhatt and Khera 2006), which is important in the HG area of Finland characterized by large open fields, light soil, and strong winds often prevailing after potato planting. Straw mulch increases soil organic matter and improves soil structure, which alleviates undesirable post-harvest N-leaching by immobilization of nitrate–N after harvest (Reeves 1997; Thomsen and Christensen 2004; Döring et al. 2005).

Taken together, the results of this study obtained in small-scale experiments following the standard experimental design of field trials, as well as the experiments carried out at a farm scale in seed potato growers' crops, indicated that application of straw mulch consistently reduces transmission of PVY in the potato crops grown in the HG area of Finland. A bale chopper provided a handy solution for spreading straw mulch. The mulch did not interfere with mechanized harvesting of potato crops. Small differences in PVY incidence can be decisive in terms of the seed class to which the yield can be certified, which in turn has a great impact on the price and the economical outcome. Results suggest that in high-value seed potato production, in which incidence of PVY is low, straw mulch is a reliable, practical, and affordable control measure against the spread of PVY, at least in growing areas where vector pressure is relatively low. Furthermore, also under higher vector pressure, straw mulch is expected to reduce infection pressure, which may help to produce high-quality seed from potato cultivars expressing modest levels of field resistance to PVY.

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