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The use of chemical plant protection products in field vegetable farms in a central industrial vegetable growing area in Finland

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Progress in the reduction of environmental and health risks of PPPs (plant protection products) using Integrated Pest Management (IPM) in the EU needs to be gauged. Here, we report, for the first time, the exact quantities of PPP used in carrot, potato, swede, and fresh pea production in southwestern Finland from 2003 to 2019. Fresh peas and swede represent exceptionally low or decreasing use of PPPs, respectively. The number of treatments per field showed an increasing trend for fungicides used on potato, despite per unit area treatments having not increased. Furthermore, for carrots, insecticide and herbicide spray frequencies increased more than treatment volumes. The results of this study form a basis for analyzing ecotoxicological risks of PPP use in the studied crops because usage and spray frequencies alone do not convey the risk levels accurately. Research needs to be continued to better guide the recording of farmers' plant protection activities and corresponding analysis to verify the impacts of IPM implementation.

Key words: Integrated Pest Management (IPM), PPP usage data, plant protection product (PPP), vegetable crops

Introduction

Since 2014, the implementation of IPM (Integrated Pest Management) in conventional crop production has been mandatory for all farmers in the EU, in accordance with the National Action Plans (NAPs) of each MS (EC 2009a). The NAPs are formulated to encourage professional users of PPPs to adopt practices and products that represent the lowest risk to human health and the environment from among those available for the same pest problem. Furthermore, the EU Member States (MS) must measure the progress achieved in the reduction of risks and adverse impacts from PPP (plant protection product) use for human health and the environment (EC 2009a, EC 2019). In addition, the EU's strategy of farm-to-fork has set a goal to halve the use and risk of pesticides by 2030. This requires understanding current, location-specific quantities of chemical pesticide use and reasons for their use to make efficient plans for reducing it (EC 2020). To be able to fully apply quantitative information on PPP use for risk management purposes and draw appropriate policy conclusions, it is not only necessary to know how much pesticides are used at the national level, but also why, where, when and how they are used, in order to account for situational effects of PPP use on the environment and human health. See, for example, Andert et al. (2015), Bürger et al. (2012) and Dirksmeyer et al. (2005) on the multitude of situational factors that influence pesticide use on farms, including vegetable farms.

In 2017, over four million tonnes of PPPs were used globally, the EU accounting for about 9% (FAO 2021) and Finland about 0.1% (Finnish Safety and Chemicals Agency 2021a). In 2021, 454 active pesticide compounds were authorized in the EU pesticides database (EC 2021a). Pesticide sales data (EC 2021b) and, from 2013, also the pesticide usage data in the MS, must be collected in accordance with the Community legislation concerning statistics on PPPs (EC 2009b). However, the EU's public pesticide data still concerns only sales data (EC 2021b). Some information for PPP on-farm usage can be found only from some EU countries, e.g. Finland, where such official data are collected every 5 years from a specific number of farms. In Finland, the public data were collected in 2013 and 2018 and the next time will be in 2023. Farmers must specify which active ingredients, in what quantities (kg) and in how large field areas (ha) of each crop they have used PPPs in given years (EC 2009b). The public data do not cover information about individual products and are not location specific.

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The current paper represents the basis for quantifying the local environmental impacts of PPPs, which will be presented later in a subsequent paper. Our longitudinal study (17 years) utilizes a database that contains records of the use of PPPs on vegetable farms in southwestern Finland. Three questions were formulated for the research:

A: Which PPPs were used?

B: How much PPPs were used?

C: To what extent were anti-resistance strategies possible with the available PPPs?

The nature and amounts of PPPs used and the possibilities of managing pesticide resistance of pests with the available selection of compounds together form an important part of IPM that aims at minimizing risks of plant protection to human health and the environment.

Materials and methods

The data represent a geographically limited, but temporally extended and, for some crops, even comparatively large sample of vegetable farms, in Finland. This particular area is a significant region for industrial vegetable growing.

The database and the crops studied

The data cover chemical plant protection activities in 2003–2019 as reported from over 100 field vegetable farms in southwestern Finland. All the farms included in this study deliver their products to the local food processing company Apetit Ruoka Ltd., which is a long-established company and plays a major role in Finland for business and export. These contract farmers record the data for their plant protection activities for the contract crops they grow in the virtual system of the company. The company gave confidential rights to use the data to the Natural Resources Institute Finland (Luke) (the agreement between Luke and Apetit Ruoka Ltd. 2703/12 01 01 06/2019). For confidentiality reasons detailed in the agreement made with Apetit Ruoka Ltd., the location of an individual fields cannot be revealed. Thus, maps of the field location are not shown, even by municipalities. During the study, the database and results were discussed several times with Apetit Ruoka Ltd. experts.

Four crop species in the database provided a sufficient annual number of separate fields, with cultivation practices and pest profiles, to enable valid conclusions to be made in this study: carrot (*Daucus carota*), potato (*Solanum tuberosum*), swede (for human consumption, *Brassica napus*) and fresh pea (*Pisum sativum*, Table 1). These four crops have an established place in the consumer products of Apetit Ruoka Ltd., the majority being sold in frozen form. The contract farmers of the company have decades of experience of producing these crops under local climatic and edaphic conditions. The number of fields included in the study per year, in 2003–2019, was 49–80 for carrot (total cultivated area on average 182.0 ha year^{-1}, 11.0% of the total area of carrot in Finland annually (Natural Resources Institute Finland 2021a, b), 19–67 for potato (on average 129.0 ha year^{-1},3.8% of the total area of processed food potato), 8–18 for swede (on average 43.0 ha year^{-1}, 11.2% of the total area of swede) and 87–200 for fresh pea (on average 796.0 ha year^{-1}, 27.0% of the total area of garden pea).

The growing season usually starts in late April or early May and ends in October, depending on year, in Säkylä Finland (longitude 22.344830; latitude 61.045231), one example location for the farms in this study (database of Luke originating from the Finnish Meteorological Institute, Venäläinen et al. 2005, results not shown). In Säkylä daylight reaches 19 hours 18 minutes in the middle of the growing season (21 June 2021) (Timeanddate 2021). However, there are large differences among growing seasons in the effective temperature sum and precipitation in the study area (database of Luke originating from the Finnish Meteorological Institute, Venäläinen et al. 2005, results not shown).

Table 1. General recommendations for crop management for carrot, potato, swede and fresh pea crops in Finland (Natural Resources Institute Finland 2021c)

Crop	Sowing/ Planting (S/P) Harvesting time (H)	Emergence and early development time	Most potential need of PPPs between sowing and harvest	Recommended crop rotation scheme
Carrot	S/P: Beginning of May. H: September–October	Early development slow. Seed germination can take 21 days. Full crop green coverage rarely achieved before mid-July.	Frequent herbicide applications are needed at the beginning of growth period. At the very early development stages frequent insecticide applications are needed for sufficient psyllid control, mid-season insecticide applications are often needed for carrot fly control. Towards the end of season leaf blight injuries may increase and fungicide applications are needed for disease control.	4–5 years
Potato	S/P: The latter half of May. H: End of August to early October.	Emergence 3–4 weeks. Crop development rapid, full crop canopy achieved in early July.	Weed control normally before or soon after crop emergence. Fungicide applications against late blight at 7–10-day intervals from the beginning of July to close to the harvest.	3–5 years
Swede	S/P: Early May, sometimes re-sowing needed due to damage by e.g., flea beetles or hard rains in some loam soil types. H: October or early November.	Early development in May.	Clubroot fungus must be controlled by crop rotation. Chemical control and crop rotation against cabbage root flies. Symptoms of boron deficiency, that can make swede more susceptible to pests, are managed by cultivar selection and boron fertilization.	5–6 years
Fresh pea, frozen	S/P: Sowings are staged from the beginning to the end of June to enable synchronizing fresh pea harvesting and Apetit Ruoka Ltd. 's freezing capacity. H: End of July to late August-early September.	The growing period is only 60–80 days.	Monitoring of the pea moth with pheromone traps and pea moth management by 0-1 pyrethroid sprayings.	5–6 years

The parameters utilized in PPP use calculations

The use of PPPs by the contract farmers of Apetit Ruoka Ltd. was documented since 2003, i.e. long before similar records became obligatory for all EU farmers in 2014 (EC 2009a). The parameters utilized in PPP use calculations were: unique crop field identifiers, field area (ha), year, crop identifiers (species, product and production type), sowing/planting date, and PPP information for each application: commercial product name(s), dose rate/ha, date of application, and target weeds/pests of each application.

This database includes information on the fields where at least one PPP was used, thus we do not have information of the proportion of nil-application fields. We assume such totally untreated fields were only few as far as the key pests of each crop species are concerned. Pests tend to occur frequently in areas with a concentration of fields with such commonly cultivated crops. Crop field IDs are not revealed in the paper, in accordance with confidentiality agreements. The database was divided into two because the electronic register was renewed to make it user-friendlier after 2008. Both datasets (2003–2008 and 2009–2019) contained the same information but in the newer dataset PPPs were selected from a drop-down menu to reduce the possibility of farmers making recording errors. The study included only active ingredients (a.i.) that were applied by the growers during the growing season, and thus seed dressing products were excluded from PPP use calculations. Most of the seed material used by farmers had been treated with PPPs by the seed companies, but this information was not available in the database. Growth regulators were not used on these crops. Overall, the data used for the study contained over 6700 observations in 2003–2008 and over 17500 in 2009–2019.

Indicators

To answer research question A (Which PPPs were used?), we compared which active ingredients were used by the farmers in the database in each of the crops and which active ingredients were registered on the market (Finnish Safety and Chemicals Agency 2021b) during the entire study period 2003–2019. Also, those that could be used according to product derogations (Finnish Safety and Chemicals Agency 2021c) were included.

To answer research question B (How much PPPs were used?), the active ingredient used per hectare in kilograms, and the application frequency per a.i. per field (number of sprays per field) were calculated for each year from the database. More than one active ingredient could be sprayed on the field simultaneously when this was appropriate. In such cases when PPP was used containing more than one active ingredient or at least several PPPs were used simultaneously as a tank mix, the number of sprays was considered to be the same as the total number of active ingredients used. In addition, the number of visits to the fields during the growing season was calculated to take into consideration that one spray could, in some cases, contain more than one active ingredient.

To answer research question C (To what extent were anti-resistance strategies possible with the available PPPs?), the availability of PPPs from different 'Mode of Action' (MoA) groups was used as a proxy indicator for the risk of pesticide resistance development in the target organisms. The fewer PPPs available for rotation from different MoA groups, the higher the risk of resistance development in the target pest. The PPPs of the database were first grouped by their target organisms (fungicides=F, herbicides=H, insecticides=I) and then by their MoA. Explanations for the MoA codes can be found from the web pages of the Resistance Action Committee (Fungicide, Herbicide and Insecticide Resistance Action Committee 2021). The minimum criterion to estimate the resistance risk potential was to see if there were active ingredients from only one or more MoA groups for a given pest (Jutsum et al. 1998).

Statistical analysis

Statistical analyses were performed using the GLM procedure of the SAS Enterprise Guide version 7.15 (SAS Institute Inc., USA). Trends in spray frequencies (n) and volumes of PPPs (kg ha^{-1}) for fungicides, herbicides and insecticides over the years in each crop were examined using a regression model using year as an explanatory variable. The pest profiles and usage of PPPs on different farms, situated close to each other, are prone to be similar within each year, whereas the variation between years and over time for farms pooled over the whole area is of greater interest. Residuals were checked through figures, and in the case of skewed distributions, a logarithmic transformation was used. A significance level of $p < 0.05$ was used for all analyses.

Results and discussion

Which PPPs were used?

A total of 58 different active ingredients were used in the studied crops in 2003–2019 (Tables 2–4). There were two derogations (Finnish Safety and Chemicals Agency 2021c): insecticide chlorantraniliprole (2019) and herbicide clomazone (2014–2019) for carrot and swede.

Table 2. The most common weeds (Natural Resources Institute Finland 2021c) and the herbicides used for control in carrot, potato, swede and fresh pea crops (the database of Apetit Ruoka Ltd.), the year of registration and withdrawal from the Finnish market, and derogations of non-registered PPPs (Finnish Safety and Chemicals Agency 2021c). The substances are arranged according to their selectivity, such that the first ones are the least selective and the last the most selective compounds.

Carrot	Potato	Swede	Fresh pea	Registered in Finland since	Withdrawn in Finland
Most common target weeds					
Matricaria spp., *Chenopodium* spp., *Polygonum aviculare*, *Fallopia convolvulus*, *Elymus repens*	*Chenopodium* spp., *Fallopia convolvulus*, *Polygonum aviculare*, *Matricaria* spp., *Fumaria* spp.	*Chenopodium* spp., *Matricaria* spp., *Polygonum aviculare*, *Persicaria lapathifolia*, *Elymus repens*	*Chenopodium* spp., *Matricaria* spp., *Galeopsis* spp., *Polygonum aviculare*, *Cirsium* spp.		

Herbicides used for pre and/or post emergence spray application					
Diquat (2003–2019)	Diquat (2003–2019)	Diquat (2012–2016)	Diquat (2003)	1960s	2020
Clomazone (2014–2019)		Clomazone (2014–2019)		derogation	
Pendimethalin (2004–2019)				2003	
	Terbutryne + Terbuthylazine (2003–2004)		Terbutryne + Terbuthylazine (2003–2004)	1970s	2004
	Carfentrazone–ethyl (2013–2018)			2012	
	Metobromuron (2019)			2018	
		Napropamide (2005–2019)		2004	
		Trifluralin (2003–2009)		1970s	2008
		Metazachlor (2003–2019)		1980s	
Metribuzin (2003–2019)	Metribuzin (2003–2019)		Metribuzin (2003–2019)	1970s	
Aclonifen (2003–2019)	Aclonifen (2003–2019)		Aclonifen (2003–2019)	1990s	
Linuron (2003–2013)	Linuron (2003–2013)			1970s	2013
Glufosinate–ammonium (2003–2012)	Glufosinate–ammonium (2003–2010)			1990s	2012
	Prosulfocarb (2005–2019)			2004	
	Rimsulfuron (2003–2018)			1990s	
	Sulfosulfuron (2003–2018)			1990s	
		Clopyralid (2003–2018)		1980s	
		Pyridate (2008)		2007	
			Bentazone (2003–2019)	1970s	
			Bentazone+MCPA (2003–2019)	1970s	
Herbicides against grass weeds, mid-season spray application					
Fluazifop-P-butyl (2003–2013)	Fluazifop-P-butyl (2018)	Fluazifop-P-butyl (2019)	Fluazifop-P-butyl (2018)	1980s	
Quizalofop-P-ethyl (2003–2019)	Quizalofop-P-ethyl (2005–2017)	Quizalofop–P–ethyl (2011–2019)	Quizalofop-P-ethyl (2007–2019)	1990s	
Propaquizafop (2003–2019)	Propaquizafop (2008–2017)	Propaquizafop (2004–2013)	Propaquizafop (2019)	1990s	
Clethodim (2008–2019)				2008	
Tepraloxydim (2012–2013)				2011	2016

Products of 11 active a.i. were withdrawn from the market in Finland during the study period. There were also four a.i. that were withdrawn from the markets after 2003–2019. For example, the herbicide linuron was used on carrot and on potato (2003–2013), by spraying it before seedling emergence in the spring. On carrot, it was the second most used PPP (kg ha^{-1}) (27.7% from all PPPs), with an application frequency of 1.6 (standard deviation [SD] 0.4) times per year in 2003–2019. On potato, it was used to a lesser extent (5.4% from all PPPs), with an application frequency of 0.3 (SD 0.2) times per year in 2003–2019. The use of linuron negatively affects the germination of carrots in the subsequent 1–2 years (Heinonen-Tanski et al. 1986). Thus, currently there are usage limits on the product label. For edible vegetables, the product must not be used in successive years on the same field due to the risk of residues.

Table 3. The most common insect pests (Natural Resources Institute Finland 2021c) and the insecticides used for their control in studied crops (the database of Apetit Ruoka Ltd.), the year of registration and withdrawal from the Finnish market, and derogations of non-registered PPPs (Finnish Safety and Chemicals Agency 2021c).

Carrot	Potato	Swede	Fresh pea	Registered in Finland since	Withdrawn in Finland
Most common target insects					
Trioza apicalis, *Psila rosae*, *Lygus* spp., *Phyllotreta* spp.	Aphid species (*Myzus persicae, Aulacorthum solani, Aphis frangulae, Aphis nasturtii, Aphis gossypii, Aphis fabae, Rhopalosiphum padi, Macrosiphum euphorbiae*), *Lygus* spp.	*Phyllotreta* spp., *Lygus* spp., *Delia* spp., *Plutella xylostella*, *Pieris brassicae*, *Meligethes* spp.	*Cydia nigricana*, *Acyrthosiphon pisum*, *Sitona* spp.		
Insecticides belonging to pyrethrins and pyrethroids (*MoA 3A*)					
Esfenvalerate (2005–2019)	Esfenvalerate (2017)	Esfenvalerate (2005–2015)	Esfenvalerate (2011, 2019)	1990s	
Lambda-Cyhalothrin (2003–2019)	Lambda–Cyhalothrin (2016–2018)	Lambda-Cyhalothrin (2003–2019)	Lambda-Cyhalothrin (2003–2019)	1990s	
Alpha–Cypermethrin (2003–2019)		Alpha-Cypermethrin (2003–2015)	Alpha-Cypermethrin (2003–2019)	1990s	
Cypermethrin (2012–2019)		Cypermethrin (2013–2016)	Cypermethrin (2012–2017)	1990s	
Deltamethrin (2003–2019)		Deltamethrin (2003–2019)	Deltamethrin (2003–2019)	1980s	
Tau-Fluvalinate (2003–2019)		Tau-Fluvalinate (2003–2018)	Tau-Fluvalinate (2003–2017)	1990s	
			Pyrethrins (2015)	1970s	
Insecticides belonging to organophosphates (*MoA 1B*)					
Dimethoate (2003–2006)		Dimethoate (2003–2018)		1970s	2020
Malathion (2003–2006)				1950s	2008
Insecticides belonging to other MoA groups					
Chlorantraniliprole (2019)		Chlorantraniliprole (2019)		derogation	
Flonicamid (2019)				2018	
Thiacloprid (2015–2019)				2015	2021
Spirotetramat (2018–2019)				2016	
Paraffin oil (2019)				1980s	

Table 4. The most common diseases (Natural Resources Institute Finland 2021c) and the fungicides used for their control in studied crops (the database of Apetit Ruoka Ltd.), the year of registration and withdrawal from the Finnish market, and derogations of non-registered PPPs (Finnish Safety and Chemicals Agency 2021c).

Carrot	Potato	Swede	Fresh pea	Registered in Finland since	Withdrawn in Finland
Diseases					
Leaf diseases (*Alternaria dauci, Cercospora carotae, Mycocenrospora acerina*)	Early blight (*Alternaria solani, A. alternata*), Late blight (*Phytophthora infestans*)	Leaf diseases: powdery mildews, downy mildews	Leaf diseases (*Didymella* spp., *Peronospora viciae*)		
Fungicides sprayed against various fungal leaf diseases					
Azoxystrobin (2005–2019)	Azoxystrobin (2013–2019)	Azoxystrobin (2012–2019)	Azoxystrobin (2005–2015)	2004	
Azoxystrobin + Difenoconazole (2011–2019)	Azoxystrobin + Difenoconazole (2014)	Azoxystrobin + Difenoconazole (2014–2015)		2010	
Boscalid + Pyraclostrobin (2011–2019)	Boscalid + Pyraclostrobin (2016–2017)			2015	
	Mandipropamid + Difenoconazole (2014–2019)			2014	
Iprodione (2008–2012)				1980s	2011
Fungicides for control of potato late blight, mancozeb products for potato					
Mancozeb (2003–2019)				1953	
Mancozeb + Cymoxanil (2009–2015)				2009	2017
Mancozeb + Dimethomorph (2003–2018)				1997	
Mancozeb + Metaxyl–M (2003–2018)				1984	
Mancozeb + Propamocarb–HCl (2003–2009)				1994	2012
Mancozeb + Zoxamide (2004–2008)				2004	2017
Fungicides for control of potato late blight, fluazinam products for potato					
Fluazinam (2003–2019)				1995	
Fluazinam + Dimethomorph (2015–2017)				2014	
Fluazinam + Metalaxyl–M (2003–2019)				1999	2020
Fungicides for control of potato late blight, propamocarb-HCl products for potato					
Propamocarb–HCl + Fenamidone (2009–2019)				2008	
Propamocarb–HCl + Fluopicolide (2015–2019)				2014	
Fungicides for control of potato late blight, other products for potato					
Amisulbrom (2014–2019)				2013	
Cyazofamid (2005–2019)				2004	
Cymoxanil (2018–2019)				2016	
Cymoxanil + Famoxadone (2005–2011)				2004	2014
Mandipropamid (2008–2019)				2007	
Mandipropamid + Difenoconazole (2014–2019)				2013	

In 2020, four additional active ingredients were withdrawn from the market in Finland. These included the organophosphate dimethoate that was used on carrot (2003–2006) and on swede (2003–2018) against carrot flies and cabbage/turnip root flies, respectively. On swede it was the most used PPP (kg ha^{-1}) (44.7 % from all PPPs) that was sprayed about twice a year in 2003–2019. According to the Apetit Ruoka Ltd. experts, the use of dimethoate was discontinued even before the active substance was withdrawn from the market.

It seems that there is no equivalent compound to replace dimethoate. Lately, the company's farmers have started to use insect nets to protect swedes against cabbage root flies.

Our data showed that PPPs used in the vegetable fields correspond to those registered on the market. However, in a few fields two products were reported in the database to have been used against target pests they were not registered for. In 2014 and 2015, the fungicides azoxystrobin and difenoconazole were reported to have been used on swede in three different fields (0.3% from all use cases in the 2009–2019 database on swede). In 2014 and 2018, the same products were reported to have been used on potato in five different fields in (0.3% of all use cases in the 2009–2019 database on potato). According to the Apetit Ruoka Ltd. experts, the reason for this might have been a recording mistake made by the farmer in the register.

To minimize the effects of the most hazardous PPPs, these products have been banned or restricted by authorities (EC 2009c) due to their environmental and health effects, and many more are expected to be phased out in the coming years due to the reformed EU hazard-based legislation concerning PPPs (Robin and Marchand 2019). This way the plant protection authorities strive to reduce PPP risks through their evaluation, and thus influence the availability of PPPs and their role among plant protection methods. As an example, because some PPPs, such as linuron, are no longer used, new PPPs that have been registered in their place, which are more specific, do not therefore necessarily correspond to the same degree of environmental effects as for the previously used PPPs. Moreover, a tank mixture of the herbicides aclonifen and metribuzin is now used instead of linuron alone and thus two compounds are now needed instead of one. In addition to the use rate, the environmental impact depends on the nature of the PPP (Wustenberghs et al. 2012, Räsänen et al. 2015, Möhring et al. 2020). Consequently, environmental and health impacts of new PPPs may be different from those of the old individual withdrawn PPP.

How much PPP was used?

Amount of active ingredient (kg ha^{-1})

The highest quantity of PPPs (kg ha^{-1}) was used on potatoes, on which 34 different active ingredients at an average of 3.5 kg ha^{-1} (SD 0.6) per year were used in 2003–2019 (Fig. 1). The temporal trend of PPP used on potato was slightly increasing (slope 0.012, p <0.01). The second highest quantity of PPP was used on swede (on average 2.7 kg ha^{-1} (SD 0.8) per year with 20 different active ingredients), showing a decreasing trend (slope -0.11, p <0.01) (Fig. 1). Carrot was third, with 1.6 kg ha^{-1} (SD 0.2) per year and 30 different active ingredients (slope 0.03, p <0.001) (Fig. 1). On fresh peas, 18 different active ingredients at an average of 0.8 kg ha^{-1} (SD 0.2) per year of PPPs were used (slope 0.01, p <0.001) (Fig. 1). Thus, the trend of total amount of PPP usage decreased only on swede, but increased on potato, carrot and fresh pea. In addition, according to Apetit Ruoka Ltd. experts, no PPP residues were found from in the company's raw materials, based on results of residue analyses.

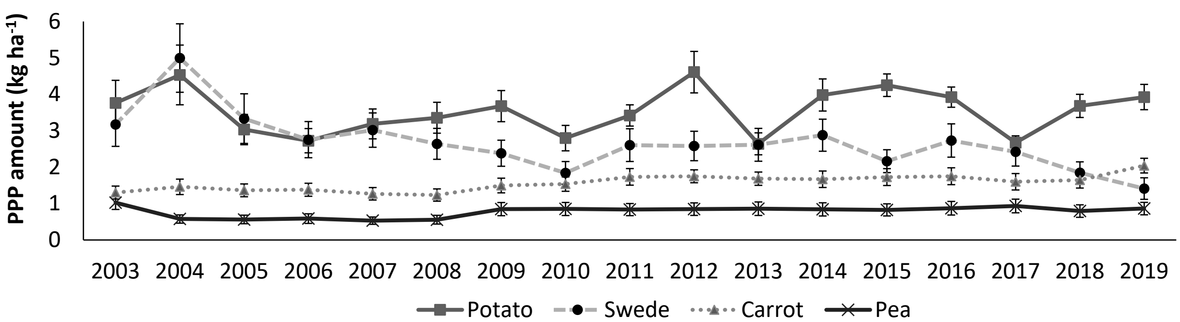

Fig.1. Total active ingredient usage of PPP (kg ha^{-1}) on potato, swede, carrot and pea crops in 2003–2019

PPP usage figures on the entire potato area in Finland in 2013 (14000 ha) were similar to our data (2.65 kg ha^{-1} vs. 2.64 kg ha^{-1}), but in 2018 (12500 ha) they were less than for our data (2.16 kg ha^{-1} vs. 3.68 kg ha^{-1}) (Natural Resources Institute Finland 2021d). For potato, in our data, fungicides (77.3% of all PPPs on potato in our data) were the most used PPPs, and herbicides (22.7% in our data) were the second most used; their order was the same for the entire potato area in Finland (Natural Resources Institute Finland 2021d). PPP usage on potato in

Sweden in 2017 was at the same level, or 3.3 kg ha^{-1}, with fungicides in the first place and herbicides in the second (Swedish Chemicals Agency 2017). While, in Scotland 9.3 kg ha^{-1} PPPs were used on ware potato, which was much more than was used in Finland or Sweden in 2018 (Wardlaw et al. 2018). Total usage for carrots in Finland, in both 2013 (1580 ha) and 2018 (1850 ha), was higher than was reflected by our data (2.21 kg ha^{-1} vs. 1.68 kg ha^{-1}, and 2.01 kg ha^{-1} vs. 1.64 kg ha^{-1}, respectively). In Scotland 7.15 kg ha^{-1} was much more PPPs than were used on carrot in Finland according to our data for 2019 (Wardlaw et al. 2019). Overall, in Finland on carrots, herbicides (87.3% of all PPPs on carrot in our data) were the most used PPPs, fungicides (6.0% in our data) were second, and insecticides (6.7% in our data) were the least used (Natural Resources Institute Finland 2021d). On fresh pea, PPP use in the whole country in 2013 (2780 ha) was higher than indicated by our data (1.27 kg ha^{-1} vs. 0.86 kg ha^{-1}), but in 2018 (4 980 ha) Apetit Ruoka Ltd. growers used slightly more PPPs (0.59 kg ha^{-1} vs. 0.79 kg ha^{-1}) (Natural Resources Institute Finland 2021d). In the whole country and in our data, herbicides (98.6% of all PPPs on fresh pea in our data) were the most used PPPs on fresh pea, while insecticides (1.2% in our data) were second and fungicides the least used (Natural Resources Institute Finland 2021d). In our data, for swede, on average 2.6 kg ha^{-1} PPPs were used during the total time period and the figure was 1.4 kg ha^{-1} in 2019. Most of the insecticides (measured in kg ha^{-1}) were used on swede (91.6% from all insecticides on all four crops) even though herbicides (52.6%) were the most used PPPs on this crop. There were no data available for overall PPP usage on swede in Finland. However, data were found from Scotland, where 1.86 kg ha^{-1} PPPs was used on swede in 2019 (Wardlaw et al. 2019). Sweden was chosen for comparison because it is a neighboring country and geographically similar to Finland. Scotland was selected to provide comparative data for swede.

Number of sprays per field

Carrot was sprayed most often (Fig. 2); on average 10.1 (SD 3.6) times per year. Note that each a.i. in such cases is considered as a single spray, as explained in the Material and methods. The number of sprayings increased from 7.7 (SD 0.7) in 2003 to 14.9 (SD 1.0) in 2019 (slope 0.67, p <0.001), mainly due to increase in the number of treatments with herbicides and insecticides (Fig. 3A). In Scotland carrot was sprayed on average 9.6 times in 2019 (Wardlaw et al. 2019). Swede was sprayed the second most often (Fig. 2), at an average of 9.3 (SD 2.1) times per year, but it was associated with a decreasing trend in the total number of treatments per field, being 10.1 (SD 1.0) in 2003, 6.6 (SD 0.7) in 2018, and 9.1 (SD 1.1) in 2019 (slope -0.23, p <0.001), mainly due to decreasing sprays of insecticides during the whole time period (Fig. 3C). In Scotland swede was sprayed on average 5.6 times in 2019 (Wardlaw et al. 2019). On potato, an average of 8.7 (SD 1.8) sprayings were made per year, and the number of sprayings increased over the time period (Fig. 2), being 7.1 (SD 0.8) in 2003 and 10.4 (SD 0.6) in 2019 (slope 0.27, p<0.001), mainly due to an increase in fungicide use (Fig. 3B). In Scotland ware potato was sprayed on average 12.6 times in 2018 (Wardlaw et al. 2018). On fresh peas, PPPs were sprayed on average 3.2 (SD 0.6) times per summer, which remained close to this level in all years (slope 0.06, p<0.001), (Fig. 2). The number of visits per field was smaller than the number of PPP sprayings because more than one active ingredient per visit was sometimes sprayed per field (on average per year on carrot 98%, potato 79%, swede 97% and pea 98%).

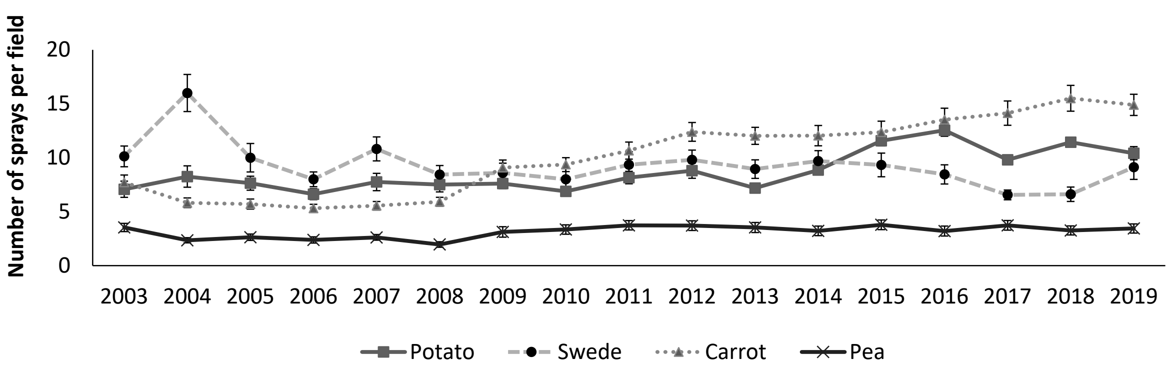

Fig. 2. PPP application frequency per active ingredient per field (number of sprays per field) on potato, swede, carrot and pea crops in 2003–2019. Note that several different PPPs could be sprayed simultaneously as tank mixes when this was appropriate; each a.i. in such cases is considered as one spray.

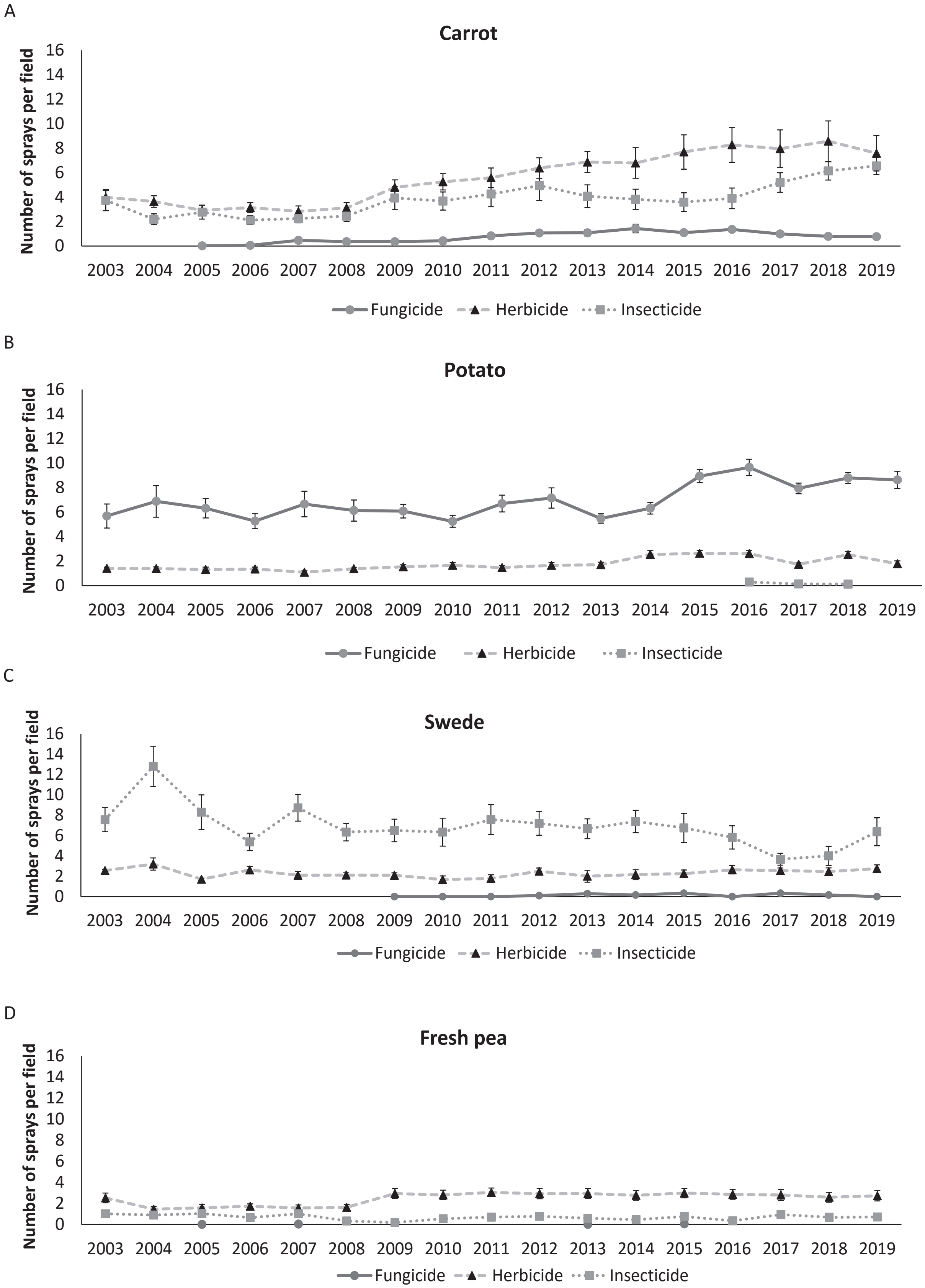

Fig. 3. PPP application frequency per active ingredient per field (number of sprays per field) for fungicides, herbicides and insecticides on carrot (A), potato, (B) swede (C) and fresh pea (D) in 2003–2019

The number of insecticide treatments per field on carrot (slope 0.21, $p<0.001$) and the number of fungicide treatments per field on potato (slope 0,19, $p<0.001$) increased, but on swede the trend for the total number of insecticides decreased (slope -0.09, $p<0.01$). Insect nets are currently perceived as the viable solution to prevent damage by carrot psyllid and cabbage root flies (Nissinen et al. 2020) due to suspected decreases in the efficacy of PPPs against these pests (Apetit Ruoka Ltd. experts). The use of nets with carrots only started in 2020 in the contract farmers of Apetit Ruoka Ltd., so there was no information available on their use for our work. In contrast, on swede, the use of insect nets against cabbage root flies began in 2012 on some farms, which we suspect contributed to the decreasing use of insecticides in this crop. However, the high purchase price of the insect nets (Munyaneza et al. 2014) and complications that they cause for weed control have slowed down the wider adoption of nets by contract farms according to the Apetit Ruoka Ltd. experts.

Fresh peas differ from the other crops in a positive respect: PPPs were used the least and the rate of use varied little over the years (Fig. 2 and 3D). The advantages of fresh peas, in Finland, might be the short growth period and a systematic long crop rotation (5–6 years) by the contract farmers according to the Apetit Ruoka Ltd. experts, which helps to slow pest reproduction and prevent pest occurrence.

The changes in the kg ha^{-1} use rates did not always reflect the changes in spray frequency (Table 5). A PPP can be withdrawn and replaced with one or two substitutes that have different use rates compared with the withdrawn ones or have a lower/higher or shorter/longer efficacy, and must therefore be used more/less often, even if use rates per treatment are similar. In addition, spot treatments can be done instead of treating the whole field, which does not affect number of treatments but reduces use rate. Thus, the use of PPPs in terms of kg per ha alone, therefore, does not describe the complete reality of PPP usage.

Table 5. The change in trends (slopes and *p*-values) for amount of active ingredient (kg ha^{-1}) of PPPs and number of sprays per field in carrot, swede, potato and pea crops in 2003–2019. The largest differences between amounts and spray frequencies are in bold.

		Amount of active ingredient (kg ha^{-1})	Number of sprays per field
Carrot	Total	slope 0.03, $p<0.001$	slope 0.67, $p<0.001$
	Fungicide	**slope 0.007, $p=0.6$**	**slope 0.07, $p<0.001$**
	Herbicide	slope 0.008, $p<0.05$ (0.048)	slope 0.38, $p<0.001$
	Insecticide	**slope 0.02, $p<0.001$**	**slope 0.21, $p<0.001$**
Swede	Total	slope -0.11, $p<0.01$	slope -0.23, $p<0.001$
	Fungicide	slope -0.0003, $p=0.8$	slope -0.0003, $p=0.2$
	Herbicide	slope -0.005, $p=0.8$	slope 0.0004, $p=0.3$
	Insecticide	**slope -0.103, $p<0.001$**	**slope -0.09, $p<0.01$**
Potato	Total	slope 0.012, $p<0.01$	slope 0.27, $p<0.001$
	Fungicide	**slope -0.02, $p=0.06$**	**slope 0.19, $p<0.001$**
	Herbicide	slope 0.03, $p<0.001$	slope 0.07, $p<0.001$
	Insecticide	slope 0.0008, $p=0.8$	slope -0.08, $p=0.2$
Pea	Total	slope 0.01, $p<0.001$	slope 0.06, $p<0.001$
	Fungicide		
	Herbicide	slope 0.02, $p<0.001$	slope 0.08, $p=0.3$
	Insecticide	slope -0.006, $p<0.001$	slope -0.01, $p<0.01$

Pesticide resistance management

We assumed that if there were active ingredients only from one MoA group to be used against a pest, it would mean a higher risk of resistance development (Jutsum et al. 1998). Products from more than one MoA group would mean the risk of resistance development was smaller. This is, of course, a crude estimation for a proxy of the risk of resistance development because its speed is influenced by several factors associated, among other things, with the compound, the target pest and its biology, success of coverage of the crop by the application, and the number of repeated applications (van den Bosch et al. 2014, Beckie et al. 2021, Corkley et al. 2022).

There are indications of insecticide resistance development in the carrot psyllid to pyrethroids that were, for a long time, the only MoA group available against this pest on carrots (Fig. 4). The data on the increase of insecticide treatments against the carrot psyllid are supported by the comments of experts from Apetit Ruoka Ltd. According to them, carrot psyllid in particular has been causing increasing problems recently, and a suspicion of resistance development was expressed in the review by Jalli et al. (2019). Scientific evidence on insecticide resistance in field vegetable pests in Finland dates, however, to as long back in time as the 1980s, when cabbage root fly (*Delia radicum*) maggots were shown to be resistant to dimethoate (Varis and Dalman 1980). In the absence of sufficient availability of PPPs with differing MoAs, crop rotation can be used to reduce the need for insecticide applications, but its success will vary according to dispersal ranges of insect pest species. For example, cabbage root flies disperse 2–3 km (see Helenius 1997, and references therein), but carrot flies disperse only 50–100 m/day. Even so, to get effective results, the distance between the old and new crop fields may need to be a kilometer or more to avoid infestations of the new fields by the carrot fly (Collier et al. 2003, Finch and Collier 2004).

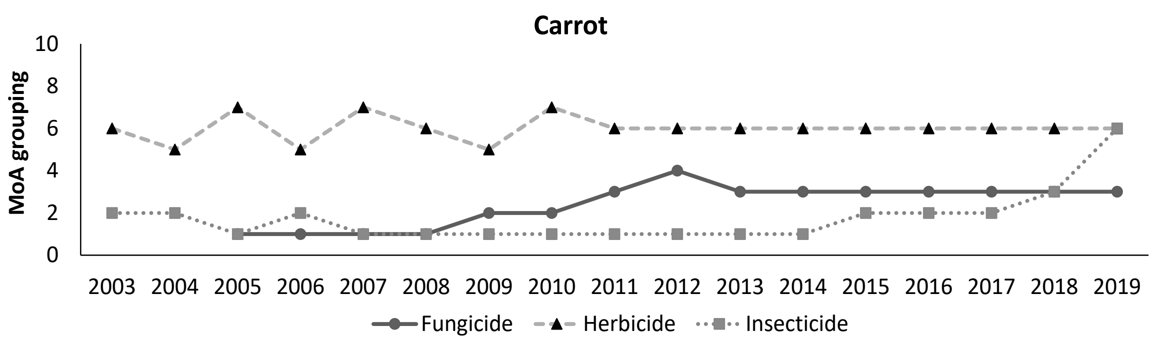

Fig. 4. The number of different MoA groups for fungicides, herbicides, and insecticides used on carrot in 2003–2019

In the last few years, insecticides other than pyrethroids from four other MoA groups (Table 3) were used on carrots against the carrot psyllid. This could decrease the resistance risk in the longer run if the newer PPPs are effective against the pest. According to the Apetit Ruoka Ltd. experts, the growing season of 2020 was the first when carrot producers used nets against insect pests of the crop. The efficacy of the nets was recently shown by Nissinen et al. (2020). Insect nets have also been used on swede during recent years, according to the experts of Apetit Ruoka Ltd. This could explain the decreasing trend in the frequency of insecticide use on swede (Fig. 3C).

The four crops harbor different weeds, and there were herbicides from several MoA groups available for all crops during the study period. Even so, we showed earlier that on carrots the number of herbicide treatments increased during the study period (Fig. 3A). The reasons for this are unclear to date. However, some reasons, in addition to resistance, could be agronomic in nature, for example insufficient coverage of weed spectrum by herbicide treatments or unfavorable weather conditions following a treatment, or newly registered active ingredients with lower overall efficacy. There are proven observations of resistance in some weed species against herbicides in Finland, including sulfonylurea-resistant *Stellaria media* in cereals (Uusitalo et al. 2013), but research is lacking on herbicide resistance in weeds that are common in vegetable crops. Such research should be a future priority.

The frequency of spraying potato has exhibited an increasing trend, according to our data, from 2014 onwards (Fig. 2 and 3B). Fungal diseases, and particularly late blight (*Phytophthora infestans*), must be regularly controlled in potato, but fungicides from different MoA groups were available for rotation to slow down resistance development. In Finland, resistance in late blight of potato has been found only for the fungicide metalaxyl at the end of the 1990s (Hermansen et al. 2000). Due to the earlier start of epidemics, and soil-borne inoculum becoming the prevalent primary infection source of late blight, which is associated with lack of proper crop rotation, the use of fungicides against late blight in potato increased four-fold in Finland between the 1980s and 2002 (Hannukkala et al. 2007). The number of fungicide treatments per field has increased more than the number of visits per field, which indicates that tank mixes of two or more active ingredients, with more selective target action, have become more common, and achieve good control of early and late blight. Forecasts for late blight are not commonly used in Finland because the time window to treat potato crops is very narrow, due to the shortness of the growing season. The disease needs to be controlled prophylactically before any symptoms occur in the crop, and a false negative decision would, with a high level of certainty, result in serious crop losses (Cooke et al. 2011). Thus, subjective risk probability, conditioned for example by the frequent occurrence of the disease in previous summers that were conducive for late blight development, can override the more objective risk probability.

Even when using forecasts, the uncertainty regarding development of such serious pests can prompt growers to spray, despite the forecast recommending the opposite (Möhring et al. 2020).

The reasons for the trends in increased numbers of insecticide and fungicide treatments for carrot and potato, respectively, were deemed different: suspected resistance to pyrethroids in the case of the carrot psyllid, but the withdrawal of broad-spectrum fungicides and their replacement with more selective ones in the case of potato, resulting in more frequent sprayings because different chemicals are needed for late and early blight. The latter reason might have contributed also to the increased use of herbicides in carrot when the broad-spectrum herbicide linuron was phased out from the market and more selective herbicides replaced it.

Conclusions

Our results are the first to report exact quantities of PPPs (plant protection product) used in Finnish vegetable crops over a long time period (17 years) in southwestern Finland. PPP use reflected specific protection needs of each crop. The number of treatments per field showed an increasing trend for insecticides and herbicides in carrots and fungicides in potato, for different reasons. Fresh peas and swede represent exceptionally low or decreasing use of PPPs, respectively, again for different reasons: a short growth period and a long crop rotation (5–6 years) for peas, and mechanical insect control for swede. In addition, despite the change in trends of PPP treatment frequencies, total treatment amounts (kg ha^{-1}) did not always behave similarly.

The possibilities for rotating different active ingredients to control weeds and fungal diseases, within and between years, was considered relatively good. Resistance problems were not experienced by farmers and were not the reason for increased use rates of PPPs in potato. This conclusion should be supported by research on the occurrence of actual resistance, to exclude agronomic reasons and reasons associated with increases in the number of treatments due to selectivity issues of PPPs in recent years. For insecticides, rotation possibilities in carrots have been extremely limited for a long time due to very restricted availability of active ingredients from different MoA groups. Inclusion of non-chemical options, however, may not be considered feasible by growers for logistical and cost reasons until resistance problems become very severe and force the uptake of non-chemical methods. It has been shown that economic characteristics (profit orientation, agricultural income, technological investment behaviour and farm labour) have the strongest effects on both uptake and intentions to take up novel technologies (Toma et al. 2018). From the farmer's perspective, getting costs of a new technology covered would be a strong incentive for its adoption, but often this has been difficult in cases of adopting IPM technologies that are more costly than chemical PPPs (Lefebvre et al. 2015).

Kilogram-based use of PPPs is a central starting point when evaluating ecological and social impacts of IPM (Integrated Pest Management) through such parameters as residues in the environment, products and drinking water. Spray frequencies complement the information on pesticide loads: how often, under what kind of conditions and in which combinations of active ingredients is the environment exposed to PPPs. Spray frequency also influences the risk of resistance development in target pests. According to Apetit Ruoka Ltd. and their residue analyses, no residues of PPPs have been found from the company's raw materials. This criterion indicates that the use of PPPs in the company's contract farms has been successful according to the principles and practices of IPM. In addition to this, PPPs have been used according to the principles of resistance management whenever PPPs from more than one MoA group have been available to control a certain pest. Resistance problems are suspected, however, in some pest species for which PPPs from only one MoA group have been available for a long period of time. In some farms, such limitations have resulted already in the uptake of non-chemical control methods despite the higher costs and increased labor requirements.

In some crops the kg ha^{-1} use of PPPs had decreased, but the number of sprays per growing season had increased. From the point of view of IPM impacts, such development is not neutral: the use of several selective PPPs in a row can have more detrimental environmental impacts than one treatment with a less-selective PPP. Furthermore, an increase in spray frequencies can reflect resistance development in pests. Thus, kg ha^{-1} use or spray frequency do not directly indicate the extent of risks of PPP use to the environment and/or human health. The use of risk indicators that consider the toxicological characteristics of PPPs is thus desirable for obtaining an accurate picture on the sustainability of PPP use. Such information is currently lacking from the farms monitored in this study and from regions where the farms are located. In addition, the discrepancy between the use rates (kg ha^{-1}) and the number of treatments per field, combined with the fact that treatment frequencies are influenced by various factors, indicates that individual quantitative measurements alone do not necessarily accurately reflect the level of implementing IPM principles when using PPPs as part of an IPM program.

Results of the current study will be employed to calculate ecotoxicological risks of PPP use in vegetable crops in the study areas. Such analyses would benefit from information on farm-level PPP use and ecotoxicological risk evaluations in similar crops in other parts of Finland and in other European countries. Such future research needs serve the better understanding of ultimate ecological and social impacts of IPM that are not captured solely through kg ha^{-1} use or spray frequencies of PPPs. Lastly, the use of different non-chemical control methods would be an important addition to such databases as were used in our study because such data would help in understanding why PPP use is changing. Research needs to be continued to better guide the recording of farmers' plant protection activities and their analysis to verify the impacts of IPM implementation.

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