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ORIGINAL PAPER

Long-term yield trends of insect-pollinated crops vary regionally and are linked to neonicotinoid use, landscape complexity, and availability of pollinators

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Abstract Time series data on crop yields for two main wind-pollinated crops (barley and wheat) and for three crops benefitting from insect pollination (turnip rapeseed, caraway, and black currant), were compiled from official agricultural statistics. In Finland, these statistics are available at aggregate national level, and at the level of each of the 15 provinces of the country. Yields of wind-pollinated crops have steadily increased in Finland, while yields of insect-pollinated crops have been highly variable. The largest crop benefitting from insect pollination is turnip rapeseed, which shows first a clear tendency to increased yields from 1980 to 1993, after which there has been a continuous decline in yields at the national average level. Regionally, the trends in turnip rapeseed yield show large variation, so that in six provinces of Finland, the trend has been significantly decreasing; in five provinces, there has been no significant trend; and in two provinces, there has been a significant linear increase in yields. Yield trends in the two other insect-pollinated crops, caraway and black currants, show similar trend variations. However, at the national average level, caraway yields show no significant trend, while black currant yields have increased during the past 6 years. The possible impact on the trends of insect-pollinated crops of three explanatory variables was analyzed. Significant linear correlation was found between the yield trends (slope of the trends) in rapeseed, and the extent of using neonicotinoid seed dressing in the provinces; the magnitude of yield decline in turnip rapeseed increased, as the use of neonicotinoid seed dressing increased. Similar significant linear correlation was found for the magnitude of yield decline in turnip rapeseed and the complexity of the agricultural landscape in each province; yield trend changed from negative to positive as the proportion of agricultural land of the total terrestrial land area declined from 28% to below 10%. The availability of honey bee colonies with respect to the growing area of crops benefitting from insect pollination also had a linear, significant impact on turnip rapeseed yield trends: yields tended to decline in provinces, where the supply of managed pollinators with respect to demand was low, but tended to increase in provinces, where the number of honey bee colonies were over 30% of the estimated demand. As neither the landscape complexity (proportion of arable land of total terrestrial land area), nor the number of honey bee colonies for pollination have changed significantly over the past 10–20 years, these factors cannot explain the observed differences in the yield trends of the examined insect-pollinated crops. It appears that only the uptake of neonicotinoid insecticide seed dressing about 15 years ago can explain the crop yield declines in several provinces, and at the national level for turnip rapeseed, most likely via disruption of pollination services by wild pollinators.

Keywords *Brassica rapa* · *Carum carvi* · *Ribes nigrum* · Pollination deficit · Pollinator decline · Finland

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Introduction

While there is abundant evidence that pollination deficits can affect the yield levels of insect-pollinated crops (e.g., Bartomeus et al. 2014; Schulp et al. 2014; Potts et al.

2016), the evidence on whether there actually are yield declines due to shortage of pollinators is ambiguous (e.g., Aizen et al. 2008, 2009; Calderone 2012; Breeze et al. 2014; Sandhu et al. 2016). Although pollinator declines have been reported at large scale at least since 2006 (Biesmeijer et al. 2006; Potts et al. 2010), few attempts have been made to study yield trends of insect-pollinated crops to see whether yield declines actually have taken place (Aizen et al. 2008; Calderone 2012). The existing studies have been made on large, aggregated datasets, which may be insensitive to possible changes in the level of delivery of pollination services, and more importantly, may not include comparators, where pollination of these crops is at an optimal level.

A further complication in analyzing the role of potential pollinator declines in crop yield trends is the relative contribution of managed pollinators (usually honey bees) vs. wild pollinators (e.g., Garibaldi et al. 2013; Kennedy et al. 2013; Gaines-Day and Gratton 2016; Rader et al. 2016); beekeepers can compensate for honey bee colony losses by obtaining or producing new colonies, and in areas with abundance of wild pollinators, honey bee colony losses do not affect yields in insect-pollinated crops. If, however, native pollinators have declined and are scarce, and honey bees are not available to compensate at least partially (see Garibaldi et al. 2013) for the declining pollination services, yield losses should be inevitable and measurable.

Several drivers for declines in pollinator availability have been identified (e.g., Potts et al. 2010; 2016), including intensification of agriculture in general, and the use of pesticides, especially of neonicotinoid insecticides for seed dressing of crops (Godfray et al. 2014, 2015; Woodcock et al. 2016). To the best our knowledge, there are no previous studies, which would analyze yield trends of insect-pollinated crops over a longer period of time, and link them to (i) features of the agricultural landscape known to affect the availability and abundance of wild pollinators, or to (ii) changes in pesticide usage (in particular, the rapid uptake of neonicotinoid seed dressing by growers), or to (iii) the availability of managed pollinators and their ability to provide the pollination service required. The aim of our study is to provide for the first-time evidence on the dependence of long-term yield trends in three insect-pollinated crops in Finland (turnip rapeseed, black currant, and caraway) on the availability of pollinators, and how the three variables described above are associated with the differences in the observed trends. Yield trend calculations for two wind-pollinated crops (barley, wheat) in Finland are included to allow comparison with crops, in which insect pollinators do not play a role.

Our basic hypothesis is that yields of insect-pollinated crops have developed differently in different parts (provinces) of Finland during the past 10–20 years, and that the differences may be explained by a possible variation in the levels of pollination of the crops. The three factors chosen here for analysis, and possibly affecting crop pollination levels, were selected because there is a large variation in these factors between the 15 provinces in Finland. Two of the analyzed factors, i.e., landscape complexity and the availability of managed pollinators, are expected to determine the basic level of pollination services to the crops—and therefore, among other known factors such as crop management, cultivars, climate, and soil, to determine the basic yield level for each of the provinces. These factors have not changed to a large extent during the period of the study (Aakkula and Leppänen 2014), and therefore cannot explain any possible, systematic changes in crop yields (i.e., yield trends). In contrast, pesticide use in the main insect-pollinated crop, turnip rapeseed, has changed significantly during the study period with the uptake of neonicotinoid seed dressing. As these neonicotinoids have been associated with harm to pollinators (EFSA 2013a, b, c), this factor has the potential to explain possible differences in the yield trends of insect-pollinated crops.

Materials and methods

Crop yields

As the basis for all analyses here, we used crop yields per hectare for each study year. The yield data were obtained from official national agricultural and horticultural statistics, published annually as aggregate figures for the whole country, but also separately for each of the 15 provinces of the country (ELY-centers) (Fig. 1). These are currently collected and maintained by the Natural Resources Institute of Finland (Luke: http://stat.luke.fi/en/maatalous, http://stat.luke.fi/en/horticultural-statistics). Crop yields/ha for each of the main cultivated plants are given only for recent years; therefore, data for earlier years had to be calculated based on the total amount produced in the province, divided by the total area of each crop per province.

For oilseed crops, separate statistics are given for spring turnip rapeseed (*Brassica rapa* ssp. *oleifera*) and spring oilseed rape (*Brassica napus*). Turnip rapeseed (TRS) yield trend was selected for the analysis, because traditionally only a small area of oilseed rape was grown in Finland. Winter oilseeds cannot be grown reliably under Finnish conditions. Data for TRS yield/ha were obtained for years 1980-2015 as national averages, and detailed data on recent trends for each of the 15 provinces for the years 2002–2015 (14 years).

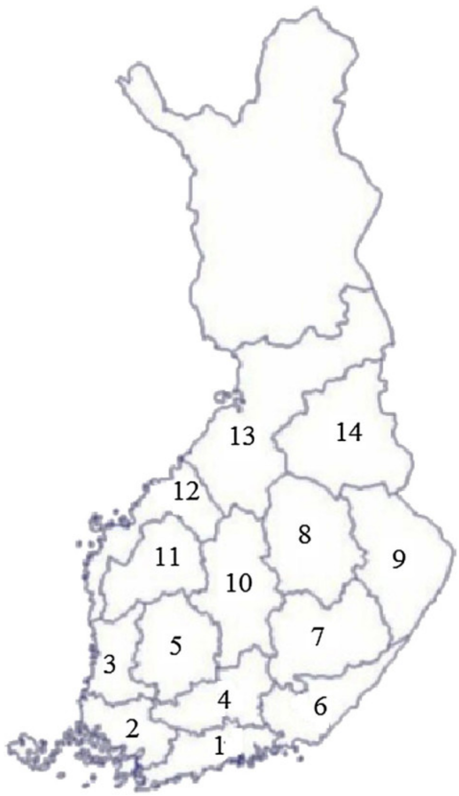

Fig. 1 Map of Finland and its provinces (ELY-Centers), used in this study, *1* Uusimaa, *2* Varsinais-Suomi, *3* Satakunta, *4* Häme, *5* Pirkanmaa, *6* Kaakkois-Suomi, *7* Etelä-Savo, *8* Pohjois-Savo, *9* Pohjois-Karjala, *10* Keski-Suomi, *11* Etelä-Pohjanmaa, *12* Pohjanmaa, *13* Pohjois-Pohjanmaa, *14* Kainuu

Detailed yield data for black currant (*Ribes nigrum*) were collated for each of the provinces (with significant area of black currants grown), for the years 2003–2015 (13 years), and for the relatively recent crop plant, caraway (*Carum carvi*), for the years 2008–2015 (8 years).

For yield trend comparison, recent data for two main wind-pollinated crops—spring barley (*Hordeum vulgare*) and spring wheat (*Triticum aestivum*)—in Finland were compiled for the years 2002–2015 (14 years).

Crop production and yield data have been collected for the official statistics in Finland in the same way for a long time, and we do not expect the time series data to contain systematic biases with respect to crop yields over time.

Landscape complexity, proximity to natural habitats, perimeter–area ratio

Farmland in Finland is in general quite fragmented, with average farmland area per farm being only about 30–46 ha depending on the province (see: http://stat.luke.fi/en/structure-of-agricultural-and-horticultural-enterprises). There are, however, large differences between the provinces of the country, so that in south-west Finland, close to 28% of the terrestrial land area is agricultural land (Table 1), while in central and eastern parts of the country less than 10% of the land is farmland. In addition, numerous waterways (lakes, rivers) dominate the landscape in much of the country, but less so in the south-west, or on the coastal plains in the west.

Further information about the agricultural landscape structure in Finland, and changes in it during our study period from 1990 to 2010, can be found in Aakkula and Leppänen (2014).

The described structure in Finland leads to increasing landscape complexity, increasing proximity to natural habitats from the fields, and much higher perimeter–area ratio, as one compares the continuum of agricultural production areas with large fields in the south-west, south, and western coastal plains, with smaller and more fragmented fields in central, eastern, and north-eastern parts of the country.

Increasing field size affects pollination services in at least two ways: (i) larger field size leads to reduced perimeter length per unit field area (50% reduction for doubling in the length of a side of a rectangular field), and (ii) distance from field edges—nesting sites for many pollinators—to the center of the field increases. Via the first mechanism, the available wild pollinators are diluted over larger areas of a crop, so that the number of potential pollinators per unit area decreases. The second mechanism affects via the effective foraging distances of wild pollinators, which range from only a few hundred meters for many solitary bees, to about 1 km for some bumble bees (Gathmann and Tscharntke 2002; Greenleaf et al. 2007). In all cases, plants close to pollinator nesting sites tend to be more efficiently pollinated (Kennedy et al. 2013; Bailey et al. 2014; Gaines-Day and Gratton 2016; Rader et al. 2016).

In our study, we condense the above discussed factors into one measurable metric: proportion of arable land of the total terrestrial land area in the province (Table 1), as a proxy for the ecological and habitat factors expected to benefit the ecosystem services provided by natural pollinators.

Pollinator availability

In the absence of managed pollinators, all pollination benefits to insect-pollinated crops must come from the ecosystem service by wild pollinators. We have no measure available on the extent of the pollination ecosystem service to insect-pollinated crops in Finland. If wild pollinators are scarce, managed pollinators may compensate to some extent—but not fully (Garibaldi et al. 2013)—the loss of natural pollinators. If wild pollinators already provide full pollination service to the insect-pollinated crops, adding

Table 1 Provinces of Finland included in the study (see Fig. 1), and their characteristic metrics

Province	Arable land in % of total land area	Area of crops using neonicotinoid seed dressing (1000 ha)	Proportion of pollination need in %, supplied by honey bees
1	20.4	23.4	7.7
2	27.7	44.6	3.9
3	18.3	14.7	10.2
4	18.4	29.8	4.8
5	13.1	13.5	10.8
6	13.1	12.7	4.6
7	5.3	1.2	44.3
8	8.9	2.2	41.3
9	4.8	2.2	55.0
10	6.1	2.9	40.3
11	18.4	18.6	2.7
12	15.3	12.4	6.1
13	6.3	3.8	5.1
14	1.5	0.1	24.5

"Arable land in % of total land area" indicates the percentage of terrestrial land area in each province, which is used as agricultural field. "Area of crops using neonicotinoid seed dressing" gives in ha the total area of oilseed *Brassica*s and sugar beet, grown in the province in 2014. "Proportion of pollination need in % supplied by honey bees" refers to the proportion of *Brassica* oilseed crops (in %) that could theoretically be pollinated by the number of honey bee hives available in each province

honey bee colonies will not provide any additional yield benefit. If there is a pollination deficit due to inadequate numbers of wild pollinators, increasing the proportion of honey bee hives (with respect to the pollination needs of insect-pollinated crops) should provide yield benefits to the growers, and thus, increase yields.

In order to get an idea of the importance of managed pollinators in Finnish agricultural systems, we analyzed the possible influence of managed pollinators on crop yield trends by comparing the yield trends to a proxy measure of managed pollinator availability. This proxy measure was obtained by comparing the known availability of managed honey bee hives within each province, with the growing area of insect-pollinated crops in that province.

The number of honey bee hives in each province was obtained from the Finnish Beekeepers' Association (SML, Tuula Lehtonen 2013, personal communication). The SML data cover about 75% of the actual number of hives, as not all beekeepers report their hives. As a proxy for the area of insect-pollinated crops, we used the total number of hectares in each province for *Brassica* oilseed crops. In all provinces, these are by far the most widely grown insect-pollinated crops. As a basis for the calculations, we consider that each hectare of oilseed *Brassica*s will need two honey bee hives for ensuring proper pollination (Sabbahi et al. 2005; Breeze et al. 2014). The final proxy measure of managed pollinator availability was therefore the proportion (in %) of oilseed *Brassica* crops in each province, which could theoretically be pollinated by the honey bee colonies kept by beekeepers in that province.

Our proxy measure on managed pollinator availability cannot directly explain yield trend differences, as we do not know the extent of pollination service provided by wild pollinators. However, we expect that if our basic hypothesis of pollination deficiencies, at least regionally, and their negative impact on crop yields is true, then the availability of managed pollinators should show an impact on the slopes of yield trends.

Neonicotinoid seed dressing use

Two crop plants are routinely treated with neonicotinoids for seed dressing in Finland: oilseed *Brassica*s and sugar beet. Practically all fields are treated, because untreated seeds are difficult to obtain. Therefore, as a proxy for the extent of use of neonicotinoid seed dressing in each province, the total combined growing area of oilseed Brassicas and sugar beet was chosen (Table 1). Neonicotinoids in seed dressing of these crops have been widely used since their registration in Finland [imidacloprid 1997, thiamethoxam 2000, clothianidin 2008; Mervi Savela, The Finnish Safety and Chemicals Agency (Tukes) 2016, personal communication]. Even during the last three growing seasons, when the use of the three active ingredients has been restricted at the EU level (EC/485/2013), the use of thiamethoxam and clothianidin has continued in springsown turnip rape and oilseed rape in Finland based on regulation EC/1107/2009, art 53 Emergency situation in plant protection (Tukes 2015). Restriction at EU level (EC/485/2013) does not concern sugar beet.

Statistical methods

The time series data for each crop and province were smoothed by transforming the data points into centered moving averages, with a span of 3 years for caraway, 4 years for TRS and blackcurrant, and 5 years for spring wheat and fodder barley. The smoothed time series was then tested with a curve estimation procedure. The length of the time series varied between crops, and additionally some provinces/crops showed quadratic trends, or did not show a trend at all. Since the vertices ($f'(x) = 0$) of the parabolas were in many cases close to each other, the time series was split, and linear curve was refitted only into the second half of the smoothed series. Thus the period of yield data under examination was finally 2006–2015, except for caraway 2008–2015 (a recent crop plant in Finland). The regression coefficients (slopes) from each statistically significant curve were taken into further analysis with the three explanatory variables. Time series, which did not have a statistically significant trend, were included in the analysis by indicating them with a slope equal to zero. The slopes were finally regressed against the independent variables with single linear regression analysis. For all statistical calculations, the SPSS version 24.0 was used (SPSS 2015).

Results

Yields of wind-pollinated crops have steadily increased (spring wheat, spring barley) at the national level in Finland, and have increased or remained stable in almost all the provinces (Figs. 2, 3; Table 2). In contrast, yields of insect-pollinated crops have been highly variable, and some have tended to decrease over the past 10–15 years. The largest crop benefitting from insect pollination in Finland is turnip rapeseed (and increasingly oilseed rape), which shows first at the national level a clear tendency of steadily increasing yields from 1980 to 1993, after which there has been a continuous decline in yields at the national average level (Fig. 4). Regionally the trends in TRS show a large variation, so that in 6 provinces, the average yields have significantly decreased during the past decade, while in 5 provinces, there is no significant trend, and in 2 provinces, there has been a significant linear increase in TRS yields (see Fig. 5).

Yield trends in two other insect-pollinated crops, caraway and black currant, show similar variations. While for black currant in general, the yield trends are positive

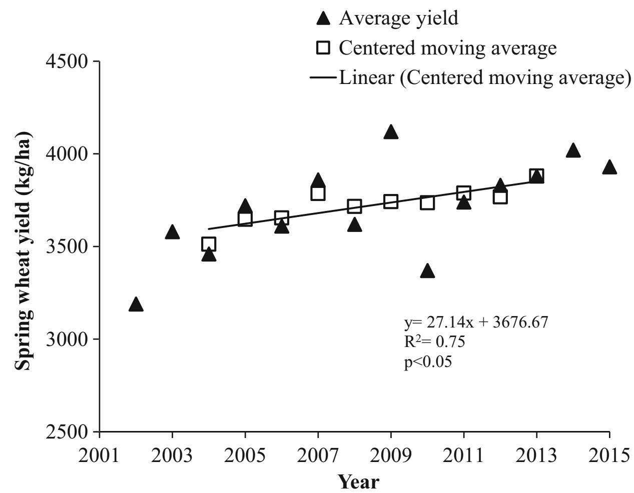

Fig. 2 Yield trends for spring wheat in Finland, in kg/ha, from 2002–2015. National averages for the whole country. Data for each province separately are given in Table 2

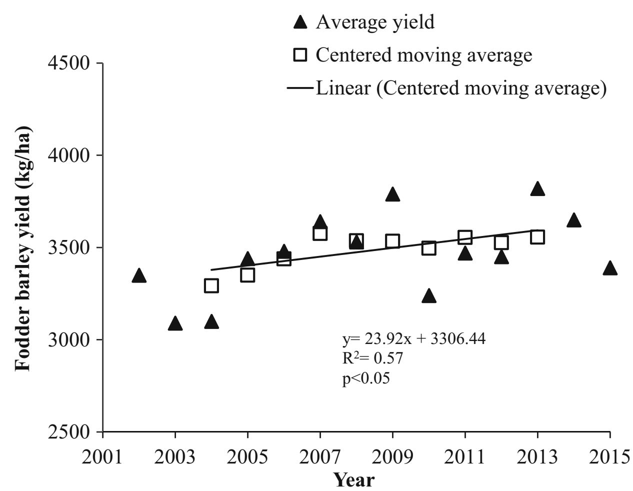

Fig. 3 Average yield of spring barley in Finland in kg/ha, national averages for 2002–2015. Data for each province separately are given in Table 2

(Table 2; Fig. 6), there are interesting contrasting yield trends in two sets of neighboring provinces: in Pohjois-Pohjanmaa (province 13, Fig. 1) on the coastal plain in the west, shows a dramatic decrease in black currant yields, while in the neighboring province to the east, Kainuu (province 14), in a diverse environment (Table 1), yields have greatly increased at the same time (see Fig. 7a, b). Exactly the same pattern can be seen for two neighboring provinces further south, in Pohjanmaa (province 12) and Keski-Suomi (province 10) (see Fig. 7c, d).

Caraway yields tend to be highly variable and seldom reach statistical significance (Table 1; Fig. 8), but nevertheless indicate dramatic decreases in some provinces (provinces 3 and 10, Satakunta and Etelä-Pohjanmaa), and

Table 2 Linear regression equations for yield trends of the different crops for each province in Finland (see Fig. 1)

Province	*B. rapa* subsp. *oleifera*			*R. nigrum*			*C. carvi*		
	R^2	Equation	p	R^2	Equation	p	R^2	Equation	p
1	0.70	$y = \mathbf{-35.12}x + 1406.42$	<0.05	0.72	$y = \mathbf{38.99}x + 367.23$	<0.05	0.23	$y = 3.00x + 540.67$	Nonsig.
2	0.74	$y = \mathbf{-24.50}x + 1367.42$	<0.05	0.98	$y = \mathbf{86.83}x + 651.76$	<0.001	0.08	$y = 4.57x + 599.43$	Nonsig.
3	0.95	$y = \mathbf{-46.07}x + 1559.58$	<0.01	0.93	$y = \mathbf{119.60}x + 456.18$	<0.01	0.67	$y = -88.00x + 1098.67$	Nonsig.
4	0.93	$y = \mathbf{-50.89}x + 1575.42$	<0.01	0.88	$y = \mathbf{76.11}x + 529.00$	<0.01	0.84	$y = \mathbf{70.48}x + 342.86$	<0.01
5	0.31	$y = -12.14x + 1359.94$	Nonsig.	0.19	$y = -6.28x + 973.51$	Nonsig.	0.92	$y = \mathbf{70.48}x + 216.19$	<0.01
6	0.75	$y = \mathbf{-48.86}x + 1401.83$	<0.05	0.73	$y = \mathbf{9.35}x + 324.15$	<0.05	Insufficient data		
7	0.67	$y = \mathbf{30.86}x + 1058.67$	<0.05	0.78	$y = \mathbf{35.29}x + 1181.88$	<0.05	Insufficient data		
8	0.19	$y = -7.36x + 1243.23$	Nonsig.	0.74	$y = \mathbf{61.23}x + 1189.73$	<0.01	0.00	$y = 1.52x + 566.48$	Nonsig.
9	0.80	$y = \mathbf{52.14}x + 543.40$	<0.05	0.83	$y = \mathbf{53.70}x + 778.13$	<0.05	Insufficient data		
10	0.65	$y = -46.50 \times 1545.08$	Nonsig.	0.95	$y = \mathbf{85.94}x + 1120.69$	<0.01	0.83	$y = \mathbf{-24.95}x + 496.73$	<0.05
11	0.86	$y = \mathbf{-28.29}x + 1380.67$	<0.01	0.91	$y = \mathbf{-57.16}x + 794.41$	<0.01	0.63	$y = 48.48x + 326.86$	Nonsig.
12	0.59	$y = 7.5x + 1332.08$	Nonsig.	0.44	$y = -7.05x + 279.75$	Nonsig.	0.70	$y = \mathbf{71.52}x + 358.70$	<0.05
13	0.10	$y = -4.29x + 1249.46$	Nonsig.	0.49	$y = -11.51x + 291.76$	Nonsig.	0.01	$y = -7.33x + 538.00$	Nonsig.
14	Insufficient data			0.83	$y = \mathbf{179.70}x + 827.08$	<0.05	Insufficient data		

Province	*T. aestivum*			*H. vulgare*		
	R^2	Equation	p	R^2	Equation	p
1	0.00	$y = -0.74x + 3595.60$	Nonsig.	0.05	$y = 7.37x + 3309.20$	Nonsig.
2	0.96	$y = \mathbf{50.23}x + 3737.87$	<0.001	0.46	$y = 16.40x + 3790.93$	Nonsig.
3	0.68	$y = \mathbf{29.66}x + 4063.20$	<0.05	0.47	$y = 35.60x + 3598.40$	Nonsig.
4	0.23	$y = 13.543x + 3674.27$	Nonsig.	0.05	$y = 6.40x + 3512.93$	Nonsig.
5	0.91	$y = \mathbf{67.03}x + 3419.07$	<0.01	0.74	$y = \mathbf{27.37}x + 3353.20$	<0.05
6	0.00	$y = -1.20x + 3488.53$	Nonsig.	0.25	$y = -27.66x + 3178.80$	Nonsig.
7	0.35	$y = 22.34x + 3088.80$	Nonsig.	0.22	$y = 17.66x + 3116.53$	Nonsig.
8	0.81	$y = \mathbf{-51.20} + 3436.53$	<0.05	0.90	$y = \mathbf{-89.37}x + 3404.80$	<0.01
9	0.28	$y = -44.23x + 2988.13$	Nonsig.	0.10	$y = 19.66x + 2921.20$	Nonsig.
10	0.03	$y = 5.71x + 3063.33$	Nonsig.	0.24	$y = -21.03x + 2889.60$	Nonsig.
11	0.86	$y = \mathbf{53.94}x + 3857.87$	<0.01	0.02	$y = 1.09x + 3911.20$	Nonsig.
12	0.62	$y = -18.97x + 4271.73$	Nonsig.	0.01	$y = -1.20x + 3866.53$	Nonsig.
13	0.79	$y = \mathbf{51.20}x + 3080.80$	0.05	0.03	$y = -6.97x + 3215.07$	Nonsig.
14	Insufficient data			0.74	$y = \mathbf{-37.89}x + 2529.60$	<0.05

Significant trends are shown in boldface. For some crops in a few provinces, there were not enough data (crop not grown) to provide a time series

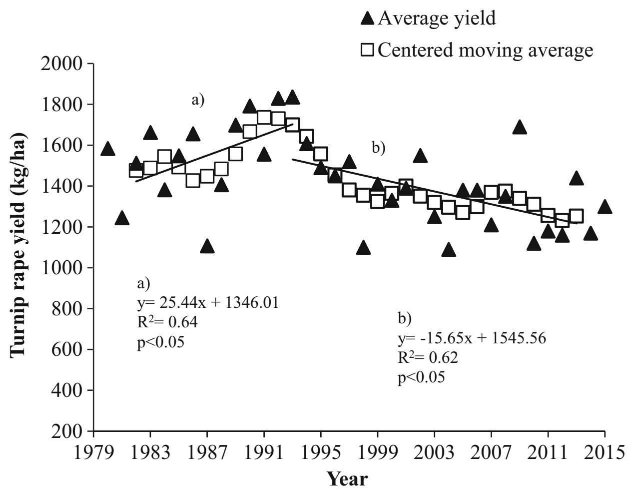

Fig. 4 Average turnip rapeseed yields in Finland (*black triangles*), and centered moving averages (*blank squares*), for the years 1980–2015. Peak yield (national average) was in 1993. Yields from 1980 until 1993 were steadily increasing (*a*), from 1993 until 2015 decreasing (*b*). Details for each province are given in Table 2

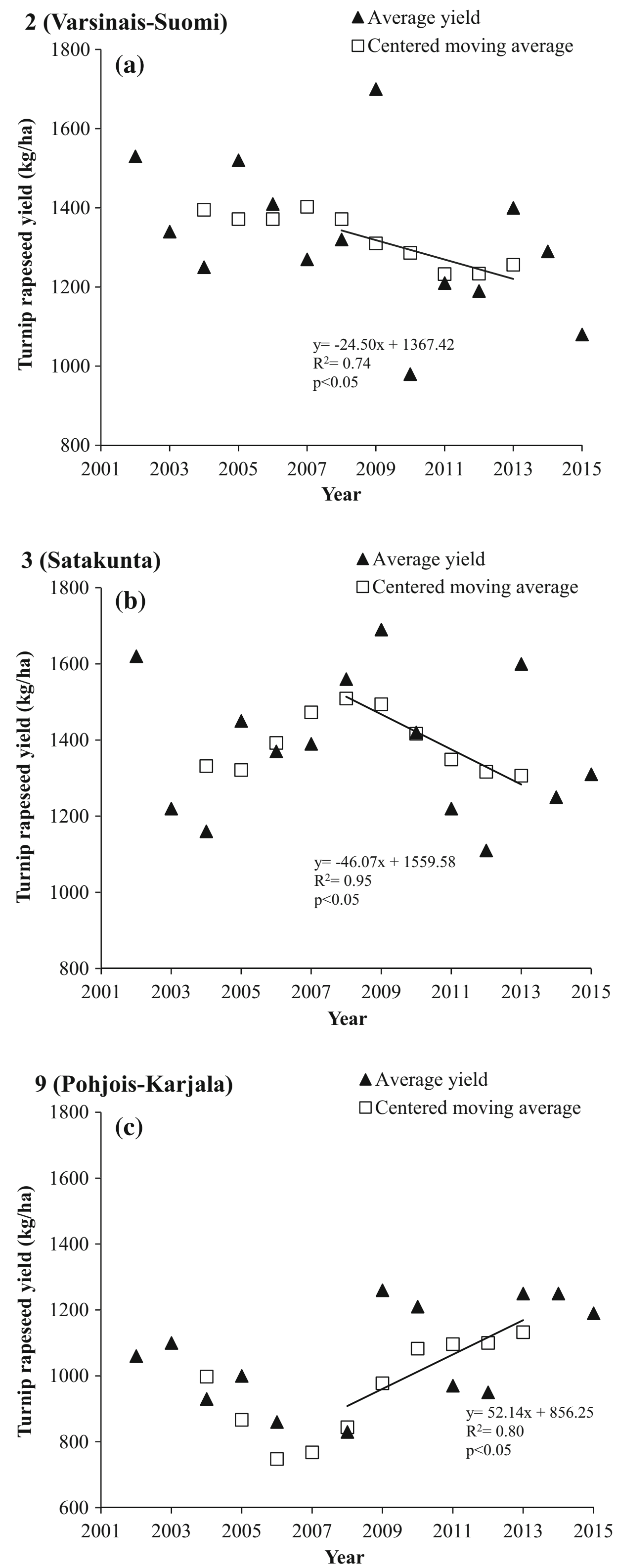

Fig. 5 Examples of yield trends in turnip rapeseed in different provinces in Finland. Province 2 (Varsinais-Suomi) (**a**) with a linear and significant decline; Province 3 (Satakunta) (**b**) with a parabolic trend but a significant linear decline from 2008 to 2015; province 9 (Pohjois-Karjala) (**c**) with a linear increase in yields since 2006

increases in close-by provinces (provinces 5 and 11, Pirkanmaa and Keski-Suomi, Table 2, Fig. 9).

An analysis of factors, which might explain the differences in yield trends between the different provinces in Finland, found a significant linear correlation between the TRS yield trends (slope of the trends) and the total use neonicotinoid seed dressing in the provinces; the magnitude of yield decline in TRS increased, as the total area of neonicotinoid crops increased (Fig. 10). In provinces where very little neonicotinoid seed dressing is used, TRS yields have continued to increase.

Similar significant linear correlation was found for the magnitude of yield decline in TRS, and the area of agricultural land of the total terrestrial land area in each province (Fig. 11): yield trend changed from negative to positive as the proportion of agricultural land area declined from 28% to below 10%.

Furthermore, the availability of managed pollinators, as a proportion of the calculated need for honey bee colonies, also had a linear, significant impact on TRS yield trends: yields were declining fastest in provinces where the supply of managed pollinators with respect to demand was lowest (3% in province 11, Etelä-Pohjanmaa, and 4% in province 2, Varsinais-Suomi), but yields were increasing in provinces where the number of honey bee hives were over 30% of the estimated need (Fig. 12). It should be pointed out that in province 11 (Etelä-Pohjanmaa), yield trends declined significantly for all the three insect-pollinated crops in this study (Table 2), and that this province had the lowest density of honey bee colonies with respect to need (2.7%, Table 1).

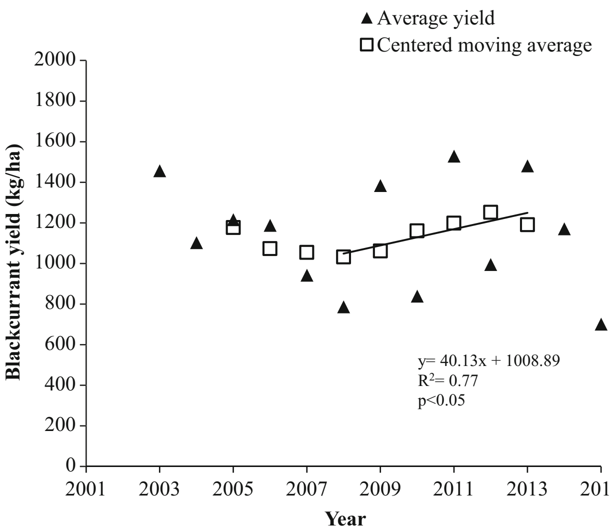

Fig. 6 Average black currant yields in Finland (*black triangles*), and centered moving averages (*blank squares*), for the years 2002–2015. Details for each province are given in Table 2

None of the explanatory variables showed significant relationship with black currant *yield trends* (data not shown). However, average *yield levels* over the whole study period in each province were significantly positively correlated with the availability of managed pollinators, which explained 52% of the variation in yield levels between provinces.

Discussion

Yield trends

Due to improved, higher yielding crop cultivars, improved production technology, and increased knowledge of yield determinants, crop yields in general tend to increase over time. We found this to be the case for the major wind-pollinated crops (wheat, barley) also in Finland. However, we found large regional variation in the yield trends of

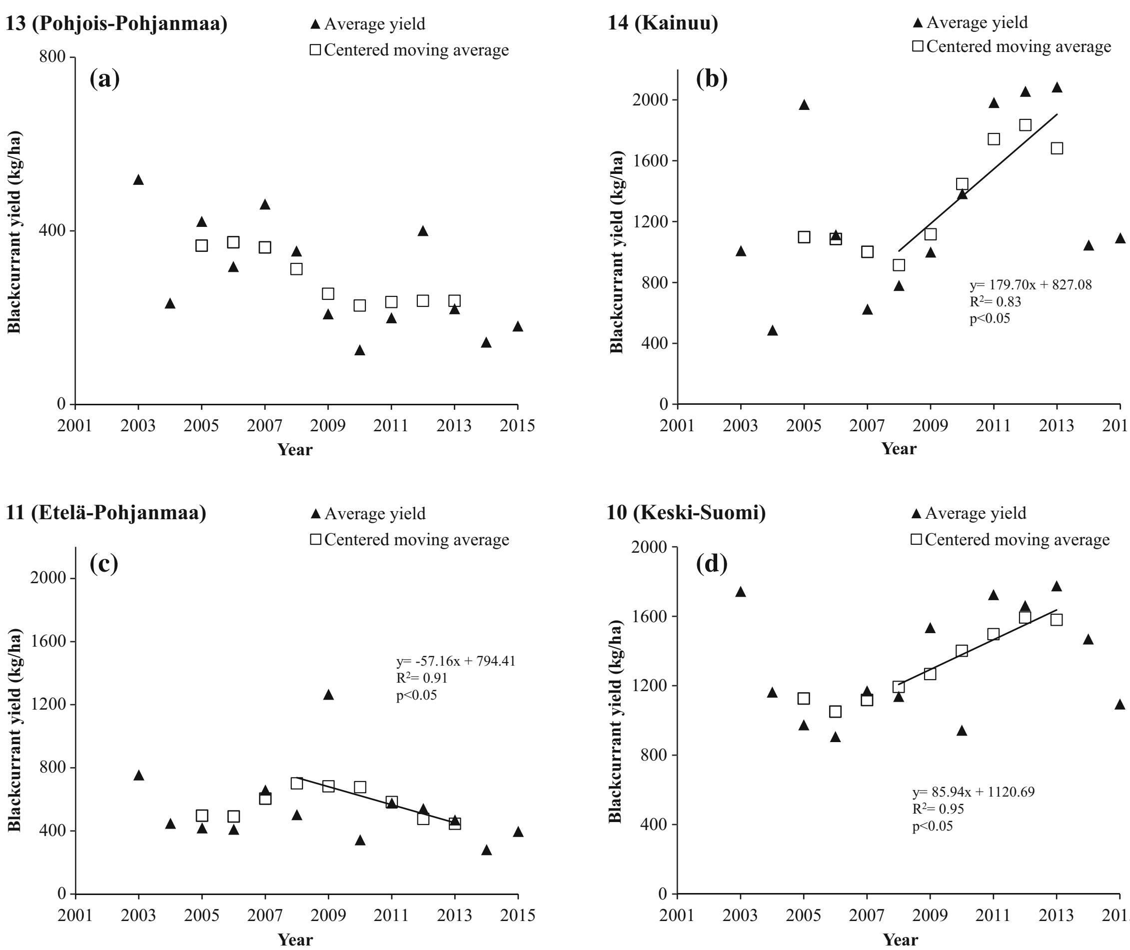

Fig. 7 Trends in black currant yields: a pair of neighboring provinces with Pohjois-Pohjanmaa (province 13) on the coastal plain in the west, having low and declining black currant yields (**a**), and the neighboring province to the east, Kainuu (province 14), with high and increasing yields at the same time (**b**). Exactly the same pattern can be seen for two provinces further south, in Etelä-Pohjanmaa (province 11) (**c**) and Keski-Suomi (province 10) (**d**)

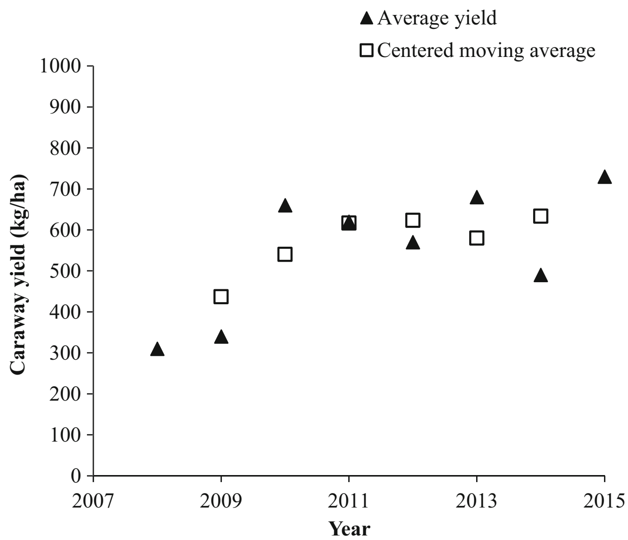

Fig. 8 Average caraway yields in Finland (*black triangles*), and centered moving averages (*blank squares*), for the years 2002–2015. Details for each province are given in Table 2

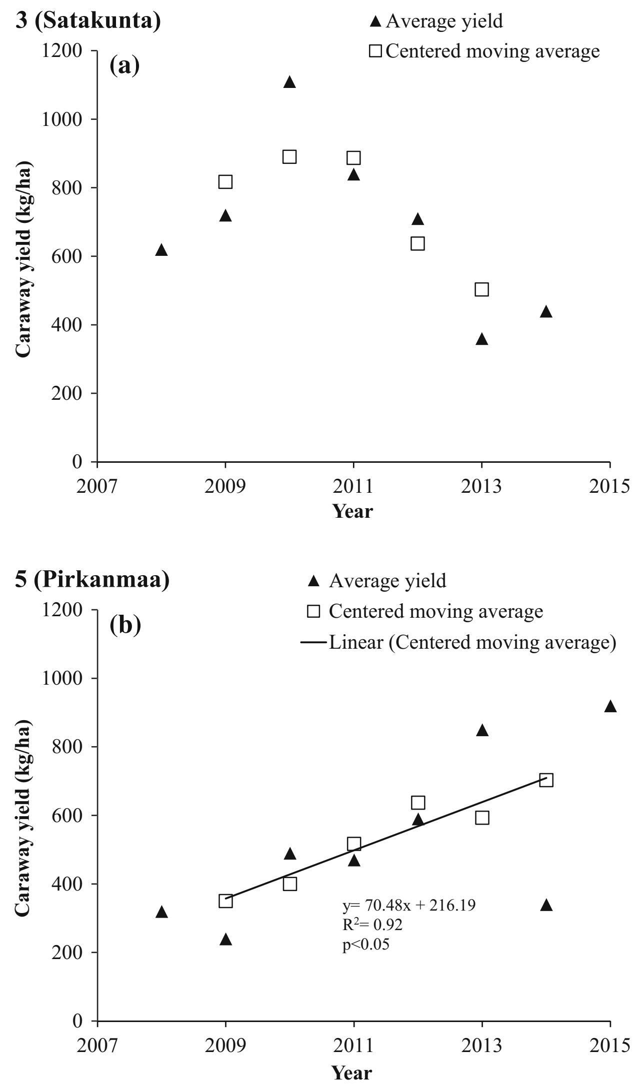

Fig. 9 Yield trends in caraway: sharp decline in Satakunta (province 3) (**a**), rising yields in the neighboring Pirkanmaa (province 5) (**b**)

insect-pollinated crops during the past 10–15 years in Finland. Alarmingly, yields of turnip rapeseed and caraway have tended to decline in the core agricultural production areas of the country. Average turnip rapeseed (TRS) yields have steadily declined at the national level for over 20 years, so that the yields have declined by 33% from the peak levels in 1990–1993.

Oilseed rape, and turnip rapeseed in particular, benefits from cross-pollination by insects (e.g., Manning and Wallis 2005; Sabbahi et al. 2005; Sandhu et al. 2016; Lindström et al. 2016a, b). Estimates of the yield benefits vary, but typically are around 20–30%, compared with the absence of insect pollinators, Yield benefits ranging from 16 to 64% have been reported (Williams 1985), and an increase by 46% was obtained when three honey bee hives per hectare were used to improve crop pollination (Sabbahi et al. 2005). The observed level of yield decline in TRS in several provinces in Finland corresponds to the reported yield benefits to TRS by adequate insect pollination, and would therefore suggest that a gradual decline of insect pollinators on the crop has taken place during the past 10–20 years, leading up to a practically complete loss of pollination benefits in recent years. This level of yield decline exceeds the combined usual yield impact of insect pests and plant pathogens on the crop in Finland (VYR 2017; Ellis and Berry 2012; Zhang et al. 2017). The most affected region is south-west Finland (Varsinais-Suomi, province 2), which produces about 25% of all TRS in Finland. At the same time, in contrast, TRS yields in many other parts of the country have either remained stable, or have increased.

The growing area of rapeseed (turnip rapeseed and oilseed rape, combined) has remained relatively stable in Finland during the study period, at about 70,000 ± 20,000 ha per year. The area was >100,000 ha only in 2 years (2006 and 2010), and only once below 50,000 ha (2013). It could be argued that large fluctuations in crop area might result in a dilution/concentration effect for pollinators; however, no such impacts could be seen on our data. Annual yield level fluctuation following large changes in sowing area do not appear to display any specific pattern in our data. The volatility in annual sowing area of rapeseed has occurred quite recently, while the yield decline already had been clear for many years.

An alternative explanation for declining yields in TRS in the early 1990s might be the switch to the so-called double-zero varieties, which initially yielded less than the previously used varieties (Ahvenniemi 1990). This could explain the distinct drop at that time (Fig. 4), but cannot

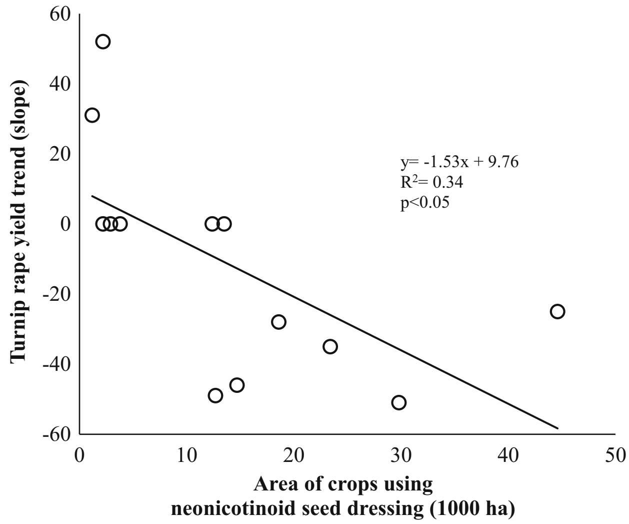

Fig. 10 Relationship between the extent of neonicotinoid seed dressing in each province, and the corresponding regression coefficient (slope) of the turnip rapeseed yield trend

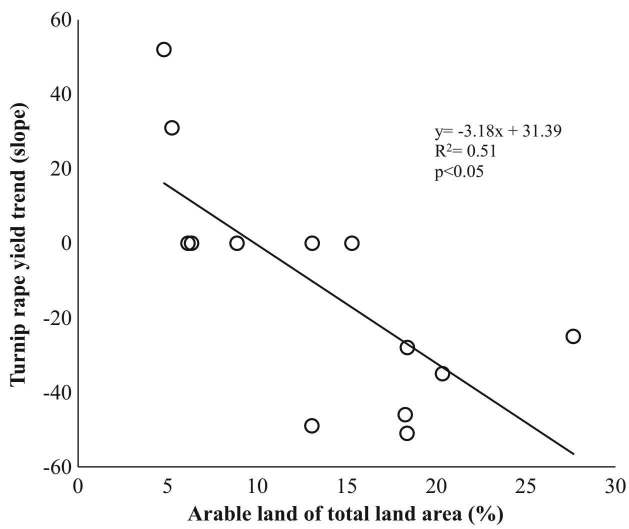

Fig. 11 Relationship between the proportion of arable land of the total terrestrial land area in each province, and the corresponding regression coefficient (slope) of the turnip rapeseed yield trend

explain the continuous decline afterwards. The 00 varieties improved, and were quickly adopted by all farmers; this factor also cannot explain why in some provinces the decline in yields continued, while in others yields did not change or even increased.

Several other factors known to affect yield levels, such as weather and climate, can play a role in determining crop yields in a given year, but are unlikely to influence yield trends in the different provinces over a longer period of time. Climate change, for example, will affect neighboring provinces in a similar way, and cannot explain the differing yield trends.

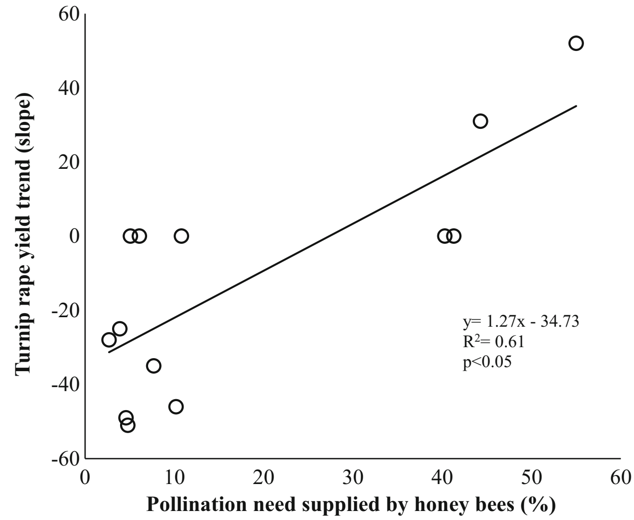

Fig. 12 Relationship between the proportion of pollination need that can be supplied by the known number of honey bee colonies in each province, and the corresponding regression coefficient (slope) of the turnip rapeseed yield trend

Yield trends in another relatively large-scale, insect-pollinated field crop—caraway—show similar variation as TRS in long-term yield trends between provinces. Caraway is considered to require insect pollination (McGregor 1976), and recent pollination field trials in Finland show that caraway yield was almost doubled when adequate pollination was ensured (Saarinen 2016). Such a clear yield response to enhanced pollination signals in our view a severe pollination deficit in the study area. Poor and declining caraway yields were found in our study in two provinces (3 and 10), while in other provinces the yields showed no trend over time or increased (4, 5, 12). The relative attractiveness of TRS and caraway to pollinators is not known, and it is possible that caraway attracts at least some pollinator groups better than TRS, and is therefore suffering less (or later) from pollinator declines than TRS.

Unlike rapeseed and caraway, currants are seldom grown in large-scale monocultures in fields of dozens or even hundreds of hectares. Currants are typically grown in smaller fields, often surrounded by natural habitats. It could be expected that any decline in the levels of natural pollinators such as bumble bees and solitary bees, will show an impact on currants later than on TRS or caraway, due to the proximity to natural habitats. A declining yield trend on currants might signal an alarming level of pollinator decline, if other production factors remain equal over time. While black currant yield levels in most provinces were increasing or stable, our study showed a tendency to declining yields in three provinces: 5, 11, 13 (Pirkanmaa, Etelä-Pohjanmaa, and Pohjois-Pohjanmaa).

Black currants are known to benefit substantially from insect pollination (Koltowski et al. 1999). The increasing yields in most provinces of Finland would seem to indicate that insect pollinators on this crop are still providing adequate ecosystem service, even when TRS and caraway in the same areas experience yield declines likely due to inadequate pollination. Maybe more striking than the yield trends in the case of black currants are the huge differences in yield levels between the provinces. Province 14 (Kainuu) is exceptional in this respect and provides currently yield levels much higher than most other provinces (two–fivefold, as compared with several other provinces). Pollinator availability appears be an explanation to these already very high and continuously rising yield levels, as berry growers in Kainuu for many years have actively promoted wild pollinators, and engage pollination services by managed honey bees as needed on their crops (Reima Leinonen, ELY-Center Kainuu, personal communication, 2016). Our data show that managed pollinator availability is significantly correlated with black currant yield levels, and explains 52% of the variation in yield levels.

Possible role of neonicotinoid insecticide seed dressing

The contribution of neonicotinoid insecticide seed dressing to pollinator decline remains controversial (Potts et al. 2010, 2016; Blacquière et al. 2012; European Union 2012; EFSA 2013a, b, c; Godfray et al. 2014, 2015). Obtaining conclusive evidence of neonicotinoid impact on pollinator populations and on pollination ecosystem service levels has been elusive (European Union 2012; FERA 2013; Woodcock et al. 2016). A study in Finland with honey bees on oilseed Brassicas, like numerous similar studies in other countries, could not establish any clear impact on honey bee colonies foraging on neonicotinoid seed-dressed fields (Ketola et al. 2015). However, high levels of neonicotinoids in the nectar, pollen, and in bee products were found, such that the total residue levels of thiametoxam and chlothianidin resulted in an estimated exposure close to the chronic and acute sublethal risk limits reported in the literature (Ketola et al. 2015). It cannot be excluded that this continuous exposure to neonicotinoids has gradually affected the levels of wild pollinators in provinces with the highest level of continued neonicotinoid use.

We found a significant linear regression between the magnitude of yield decline in turnip rapeseed, and the extent of neonicotinoid seed dressing use within each province. In provinces with the highest level of neonicotinoid use, the yields of TRS declined the most. The decline in yields in these provinces has been gradual but steady, and the decline started around the time when neonicotinoid seed dressing was allowed in Finland. To the best of our knowledge, this is the first study to show such a connection between neonicotinoid use and yield trends over time in an insect-pollinated crop.

In the worst affected province (province 2, Varsinais-Suomi), honey bees practically never played a significant role as TRS pollinators, because the number of honey bee hives in the province are only enough for pollinating effectively about 4% of the TRS crop area. Therefore, the pollination of TRS crop in the province must have relied on wild pollinators in the past decades. Recently it has been shown that the role of wild pollinators, including nonbee pollinators, has been underestimated as crop pollinators (Rader et al. 2016). Our result implies that during the past 15–20 years, the apparent and increasing pollination deficiency is the result of declining levels of wild pollinators on the crop. As there are no long-term monitoring results available on populations of wild pollinators, or their visitation rates on TRS or on any other crop in Finland, this result lacks support from evidence on the ground. However, until other, more plausible explanations are offered, we consider our result as the best explanation available.

Landscape complexity

It is widely acknowledged that the complexity of the agricultural landscape, including proximity to noncrop areas, is critical for effective pollination services (e.g., Riitters et al. 1995; Gathmann and Tscharntke 2002; Greenleaf et al. 2007; Kennedy et al. 2013; Danner et al. 2016; Neokosmidis et al. 2016). Bailey et al. (2014) showed how distance from forest edge directly affects pollination rates in oilseed rape fields. Pollinator habitat is particularly abundant in mosaic landscapes, where the presence of green linear elements were found to increase the pollinator visitation probability by 5–20% (Schulp et al. 2014). We found a significant linear regression between TRS yield trends and our proxy measure for landscape complexity (proportion of agricultural land of total terrestrial land area in each province). It thus appears clear that in provinces where fields are relatively small and are surrounded by suitable habitats for wild pollinators, the current levels of pollination services are adequate and do not compromise the yields of insect-pollinated crops, as indicated by increasing yield trends over time. In contrast, in the most intensively cultivated parts of the country, the pollination service levels appear to be inadequate, as indicated by declining yield trends.

Availability of managed pollinators

Managed pollinators, usually honey bees, are routinely used for pollination services in many countries, to ensure adequate pollination of insect-pollinated crops. Improved pollination has repeatedly been shown to increase yields of insect-pollinated crops (e.g., Bartomeus et al. 2014; Breeze et al. 2014; Schulp et al. 2014), including oilseed rape

(Manning and Wallis 2005; Sabbahi et al. 2005). In cranberry, Gaines-Day and Gratton (2016) found that cranberry yield was strongly and positively correlated with honey bee hive density, but that this effect diminished as the proportion of woodland in the surrounding landscape increased. We found a significant linear regression between the number of honey bee hives, relative to the need, within each province in Finland, and the yield trends of TRS crops: yield trends were increasing, when the number of honey bee hives corresponded to at least 30% of the calculated need. Yield trends tended to decline significantly, when the number of available honey bee hives was less than 10% of the calculated need.

Conclusion

We established a link between the long-term yield trends in insect-pollinated crops—in particular in turnip rapeseed in Finland—to three key factors either known or expected to affect pollination success. To the best of our knowledge, our study is the first to show yield impact of pollinators at the level of aggregated yield statistics, and over a long period of time, rather than at the level of single fields in short-term, controlled experiments. The key question is, which of the three identified factors is the most important in explaining the yield trend differences, and in particular, the drastic declines in TRS yields in South-west Finland. Why has there been a dramatic change during the past 10–20 years? To the best of our knowledge, in Finland nothing else in the agricultural landscape and crop management has changed significantly during the past 10–20 years, except pesticide use: rapid uptake of neonicotinoid seed dressing at a large scale. Use of other pesticides on rapeseed crop has not changed in recent years, as the main pest, the pollen beetle *Meligethes aeneus,* can still be controlled with pyrethroids (but see Tiilikainen and Hokkanen 2008). Although the landscape complexity clearly affects the supply of pollination services, the landscape has not changed significantly in the various provinces during the past decades, and therefore cannot explain the declining yield trends. The same applies to the number of managed pollinators within each province, because the number of honey bee hives has remained approximately the same over the study period. This would indicate that the neonicotinoid seed dressing, widely practiced since their registration 10–20 years ago, is affecting negatively the levels of wild pollinator ecosystem services in the main agricultural production areas in Finland.

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