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Time trends of field vegetable yields and yield gaps in northern latitudes using a Bayesian approach

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Open-field production of horticultural crops has high economic value in Finland. Profitable production requires sufficiently high yields and good product quality. This study's objective was 1. to assess the temporal and regional variation in the yield of three field vegetables (carrot, onion, and white cabbage) in Finland and 2. to quantify the yield gap of these species in their main production regions. The analysis was based on comprehensive statistical data (2012–2021) modelled using a Bayesian approach. Time trends varied between plant species and regions. In carrot, the yield tended to remain similar between the years. In onion, some statistically significant increasing regional time trends were found, whereas in white cabbage the significant time trends were mostly negative, indicating a decreasing yield over time. The yield gap was largest in onion, but its economic value was highest in carrot. To ensure profitable and sustainable production, it is necessary to reduce the yield variation and yield gaps to control production risks.

Key words: carrot, onion, cabbage, statistics

Introduction

Open-field horticultural production in northern Europe is restricted by the short growing season. Despite Finland's northern location (between 60 and 70°N) and small population (5.60 million on 31.12.2023, OSF: Statistics Finland, Population Structure), its horticultural production is vigorous. The increasing interest in a vegetable-rich diet offers new opportunities for vegetable production. Simultaneously, climate change is causing serious threats to agriculture (including horticulture) in the main production areas in southern Europe, which stresses the importance of increasing production in northern latitudes (European Environment Agency 2019). During the 2012–2021 period, the cultivation area of field vegetables in Finland increased by 32.7% (8 616 ha in 2012 vs. 11 435 ha in 2021), while the number of enterprises producing vegetables decreased by 9.5% (1 529 in 2012 vs. 1 383 in 2021) (OSF: Natural Resources Institute Finland, Horticultural Statistics). Seventy-five per cent of the increase in the cultivation area was due to the increased area under garden pea cultivation. Garden pea is the most widely cultivated vegetable in Finland, but when production in tonnes is considered, the most important vegetable crops are carrot (*Daucus carota* L.), onion (*Allium cepa* L.), and white cabbage (*Brassica oleracea* var. *capitata* L.).

The yield of vegetable species varies between years. However, the magnitude of variation and the general trends in yield development over the years have not previously been analysed. Climate change has affected growing conditions in Finland, e.g. by advancing the beginning of the growing season, increasing its length and degree day sum (Aalto et al. 2022), and increasing the risk of droughts (Veijalainen et al. 2019). The probability of heatwaves has also increased (Ruosteenoja and Jylhä 2023). According to review by Scheelbeek et al. 2018, the impact of environmental changes on vegetable production are largely unknown but especially reduction in water availability decreases vegetable yield considerably. However, the adaptive measures needed to secure productivity in horticulture have not been widely discussed, as Bisbis et al. (2018) also noted in their review focusing on temperate European conditions.

The concept of yield gap is commonly used in studies dealing with food security, biodiversity, land use, and climate change (see Rattalino Edreira et al. 2021). Yield gap is defined as the difference between the potential and actual yield (van Ittersum and Rabbinge 1997, van Ittersum et al. 2013). It has been found that average farm yields tend to plateau when they reach 75–85% of yield potential (Lobell et al. 2009, van Ittersum et al. 2013). This plateau has been called "exploitable yield" (van Ittersum et al. 2013) or "economic yield" (Fischer 2015), defined as the "yield attained by the farmers with average natural resources when economically optimal practices and levels of inputs have been adopted while facing all the vagaries of weather". Due to different methods to estimate yield potential, it is difficult to compare yield gap results from different studies. It is also noted that the concept of yield gap is understood differently by agronomists and economists, as agronomists focus on the biophysical

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and physiological determinants of crop production, while economists emphasise the role of prices, the market, and efficiency (van Dijk et al. 2017).

Yield gaps of field crops in Finland have been estimated to be relatively high (Schils et al. 2018), and they have even increased since the 1990s (Peltonen-Sainio et al. 2015a, Peltonen-Sainio et al. 2016), despite Finland's abundant water reserves (Peltonen-Sainio et al. 2015b). Peltonen-Sainio et al. (2015a, 2016) used the data from official variety trials as the measure of genetic yield potential, which has risen consistently. The national yields of the studied crops have also increased but not as much as the genetic potential, which has caused yield stagnation or even decline.

Yield gap analysis has not been commonly utilised in vegetable production, but some examples exist: Berrueta et al. (2020, 2021) analysed the yield gaps of tomato production in Uruguay to identify the factors limiting crop yield and Kleijbeuker and Lee (2019) analysed yield gap of sweet pepper between Korea and the Netherlands. Yield gap and constraints have also been evaluated for potato, where the availability of water was regarded as a main factor limiting yields in Western Europe by expert evaluation (Hengsdijk and Langeveld 2009). To develop strategies for the sustainable intensification of horticultural production, it is necessary to obtain more precise knowledge of the yield potential and gap of different species.

This study's objectives were 1. to assess the regional time trends of the yield of the three major field vegetables (carrot, onion, and white cabbage) produced in Finland and 2. to quantify the yield gap of these species in their main production areas in Finland. The analysis was based on comprehensive statistical data.

Material and methods

Data

Production data were derived from Horticultural Statistics (Official Statistics of Finland: Natural Resources Institute Finland). Horticultural Statistics is based on an annual farmer questionnaire. The questionnaire is sent to farms whose estimated standard output (SO, see Table 1) for horticultural production is over €10 000. For smaller horticulture farms (SO lower than €10 000), yields are estimated using the respondents' average yields.

Table 1. Variables used in data selection and analysis

Variable	Categories/Units	Description
Year	2012–2021	Production year
Plant species	Carrot Onion White cabbage	Cultivated plant; the three main vegetables were selected for the analysis
Economic size (SO)	€	SO (standard output) is a monetary value of the agricultural gross production at the farmgate price [1]
Horticulture SO	€	Standard output (SO) for the total horticultural production of the farm. The estimated monetary value of the horticultural output using mean annual prices.
Region	ELY Centre	The administrative unit for economic development, transport and the environment. Finland has been divided into the 15 ELY units plus the Åland Islands.
Yield	kg	The crop yield sold or intended for sale
Area under cultivation	ha	The cultivation area of the production plant in hectares
Yield per hectare	kg ha^{-1}	The crop yield (kg) / area under cultivation (ha)

[1] EC 2009

This study focused on professional horticulture farms producing one or several of the main field vegetables in Finland: white cabbage, carrot, or onion. Yield data from 2012–2021 were analysed separately for each crop. The following filtering was performed for the original data: we excluded 1) organic farms, 2) small farms whose cultivation area of the above species was less than 0.5 ha, or the horticultural SO was less than €10 000, and 3) farms whose yield was 0 kilograms. Organic farms were excluded because of the small number of farms (in 2021 there were only 21, 53 and 65 farms growing organic cabbage, carrot and onion, respectively, in Finland), their small average growing area and the lack of price data used in yield gap estimates. After this procedure, our data accounted for (as an average over all years) 41, 47, and 66% of all farms producing onion, carrot, and white cabbage, respectively, (Table 2) in the original statistical data. The coverage of the cultivation area was much higher: 97, 94, and 96% of the total cultivation area; and 96, 99, and 97% of total production in tonnes of onion, carrot, and white cabbage, respectively (Table 2).

Table 2. Number of farms, cultivation area and total production of onion, carrot, and white cabbage in 2012–2021 in original Horticultural Statistics data (Official Statistics of Finland: Natural Resources Institute Finland) and in the filtered data used in the analyses.

		Original data			Filtered data					
Crop	Year	Number of farms	Cultivation area	Production	Number of farms		Cultivation area		Production	
			ha	1000 kg		*% of original data*	ha	*% of original data*	1000 kg	*% of original data*
Carrot	2012	352	1480	55585	151	*43*	1403	*95*	53484	*96*
	2013	363	1582	70800	154	*42*	1491	*94*	67368	*95*
	2014	361	1652	74221	157	*43*	1561	*94*	70856	*95*
	2015	346	1644	63756	152	*44*	1547	*94*	60860	*95*
	2016	326	1697	72910	156	*48*	1605	*95*	70237	*96*
	2017	312	1762	62319	143	*46*	1647	*93*	59840	*96*
	2018	286	1833	66624	152	*53*	1731	*94*	63478	*95*
	2019	288	1831	77230	139	*48*	1700	*93*	72567	*94*
	2020	274	1720	80891	133	*49*	1592	*93*	75714	*94*
	2021	256	1726	75513	149	*58*	1704	*99*	74659	*99*
	Mean					***47***		**94**		**96**
Onion	2012	443	1110	21472	150	*34*	1057	*95*	21005	*98*
	2013	435	1113	22864	152	*35*	1072	*96*	22424	*98*
	2014	423	1149	26161	157	*37*	1105	*96*	25692	*98*
	2015	380	1191	27713	151	*40*	1153	*97*	27335	*99*
	2016	337	1124	26096	137	*41*	1092	*97*	25766	*99*
	2017	341	1191	26105	136	*40*	1154	*97*	25797	*99*
	2018	312	1254	23201	134	*43*	1225	*98*	22948	*99*
	2019	311	1232	31335	141	*45*	1196	*97*	30971	*99*
	2020	285	1221	29656	132	*46*	1198	*98*	29398	*99*
	2021	282	1202	29164	130	*46*	1173	*98*	28970	*99*
	Mean					***41***		**97**		**99**
White cabbage	2012	205	556	21373	133	*65*	533	*96*	20775	*97*
	2013	209	561	21890	130	*62*	536	*96*	21360	*98*
	2014	210	591	24303	132	*63*	568	*96*	23798	*98*
	2015	188	554	20741	118	*63*	531	*96*	20150	*97*
	2016	177	544	19463	109	*62*	513	*94*	19006	*98*
	2017	166	561	22888	108	*65*	533	*95*	22234	*97*
	2018	153	547	19232	101	*66*	520	*95*	18424	*96*
	2019	147	583	22415	106	*72*	556	*95*	21759	*97*
	2020	144	578	22352	97	*67*	546	*94*	21574	*97*
	2021	128	569	19649	96	*75*	563	*99*	19550	*99*
	Mean					***66***		**96**		**97**

The variable used in the data analysis was the annual yield per hectare on each farm (Table 1). The yield per hectare is hereafter referred to as “yield”.

The data are categorised for 16 regions according to the ELY Centre areas (Centre for Economic Development, Transport and the Environment) (Fig. 1). Regions differ in growing conditions, e.g. the length of the growing season, soil type, degree day sum, and total precipitation. These growth factors are assumed to affect the yield of vegetables.

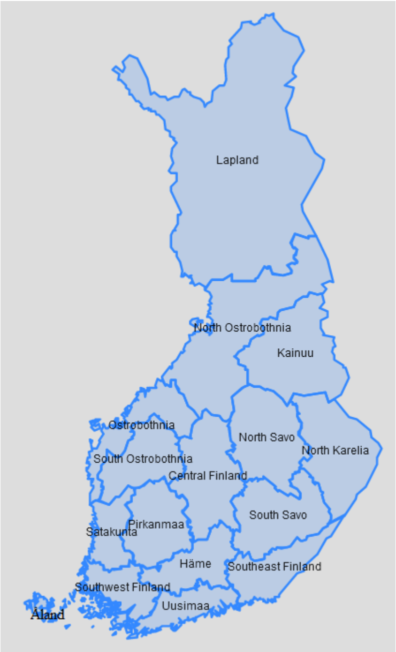

Fig. 1. ELY Centre regions in Finland

Statistical analyses

A Bayesian approach was taken to investigate the time trend in yield for carrot, onion, and white cabbage**.** Each plant was modelled separately. We were interested in general trend effects and used a Bayesian approach, which enabled direct probability interpretation and flexibility. Bayesian data analysis is a statistical approach that enables the integration of prior knowledge into the data analysis process through the use of prior probabilities. This methodology is rooted in the Bayesian theorem, allowing for direct interpretation of probabilities as measures of belief that update as new evidence is presented. One significant benefit is the continuity of analysis it supports; the posterior distributions obtained from one study can be used as priors in subsequent research, facilitating an iterative learning process. This aspect of Bayesian analysis provides a robust framework for decision-making that incorporates both past and current data, making it particularly powerful in fields where historical data or expert knowledge is pivotal.

Three separate linear regression models, one for each plant, were fitted using a normal likelihood in the form of

$$y \sim N\left(x'\beta, \sigma_j^2\right),$$

where *y* denotes mean yield per hectare, *x* denotes a p × 1 predictor matrix, *β* denotes a p × 1 parameter vector, and σ_j^2 denotes the variance where index *j* (1,...,*G*) indicates that the variance was allowed to differ between the areas. *x* includes intercept and slope terms with respect to time (2012–2021), separately for each region. The model thus allowed the investigation of a linear trend in time separately for each region. For carrot and white cabbage, *p* = 34 and *G* = 17, whereas for onion, *p* = 32 and *G* = 16.

A first-order polynomial model was fitted because it allowed the investigation of the research questions simply yet powerfully. We included a control region to aid modelling interpretability. Its value was chosen as the mean yield per hectare in 2012 over all regions for each plant, and it remained constant through 2012–2021. Treating this control level as the baseline allowed an easy comparison: significant differences of slopes between any region and the control would thus indicate either a significant increasing or decreasing trend. Moreover, significant differences of intercepts between any region and the control would indicate the starting point (2012) for differences between a region and the average mean yield per hectare.

The prior distributions for β parameters were chosen as weakly informative, $\beta_k \sim N(0, 1 \times 10^{-12})$ for k = 2,...,p

and $\beta_1 \sim N(0, 1000)$ for k = 1 (control). The variance prior distribution was formulated using precision:

$\frac{1}{\sigma_j^2} \sim InvGamma(0.001, 0.001)$ for j = 2,...,G and $\frac{1}{\sigma_1^2} \sim InvGamma(0.001, 0.001)$ for j = 1 (control).

MCMC representativeness and accuracy was assessed for both time trend models and annual variance heterogeneity models, using trace plots, Gelman-Rubin statistics (Gelman and Rubin 1992), effective sample sizes, and Raftery-Lewis diagnostics (Raftery and Lewis 1992). Posterior distributions are shown in Appendix 1 to provide information to further studies.

Statistical analyses were performed using the R software (R Core Team 2022) and packages dplyr (Wickham et al. 2023), ggplot2 (Wickham 2016), and rjags (Plummer 2022).

Yield gap analysis

Yield gap analysis was performed separately for each plant species. We focused on the three biggest ELY centres with respect to the area under cultivation (sum of cultivation area over 2012–2021). These regions were Southwest Finland, Häme, and Satakunta for carrot; Southwest Finland, Åland, and North Savo for onion; and Ostrobothnia, Satakunta, and Uusimaa for white cabbage. The annual mean yield per hectare for the highest 10% of yield per hectare farms was calculated for each crop and region. This was defined as the potential yield. Furthermore, the annual median yield was calculated. The annual yield gap was defined as the difference between the potential and median yields.

An economic indicator of the value of yield gap was calculated using annual mean prices obtained from Kasvistieto Ltd (https://kasvistieto.fi/). The price data are collected monthly from growers and packing companies, and they present the farmgate prices. The annual prices were calculated by weighting monthly prices with the monthly product quantities in the price data. The economic value of the annual yield gap was calculated by multiplying the annual yield gap (kg ha^{-1}) by the annual mean price (€ kg^{-1}).

Results

Table 3 shows the model parameter mode estimates for carrot, onion, and cabbage respectively. Fifty thousand iterations were used, based on Raftery-Lewis diagnostics to obtain stable chains and accurate estimates. Three separate MCMC chains were generated for each time trend model (50 000 iterations for carrot, 150 000 iterations for onion, and 50 000 iterations for white cabbage). Trace plots for parameters showed convergence for each chain. Gelman-Rubin statistics had values of 1. Effective sample sizes were well over 10 000, which is considered a bottom limit for inspecting 95% HDIs. Raftery-Lewis diagnostics suggested values that were well exceeded with the number of iterations used.

Time trends in yield

The yield variation of the main vegetable species in different regions and years is presented in Figures 2–4. The red lines in the figures represent the statistically significant time trends (slope probability exceeds 95%) according to the model (Table 3), whereas the blue lines denote nonsignificant time trends.

In carrot, a significant increasing time trend in yield was found only in North Savo (Fig. 2), with a slope value of 2 780, indicating an average yield increase of 2 780 kg ha^{-1} per year (Table 3). In other regions, no statistically significant time trends were observed.

In onion, significant increasing time trends were observed in Satakunta, Åland, and Southwest Finland (Fig. 3). Slope values in the model varied between 421 and 708, indicating an average yield increase of 421–708 kg ha^{-1} per year. In North Ostrobothnia, there was also a significant increasing time trend (+1240 kg ha^{-1} per year), but due to very few onion farms in the data in that region, only the observations for 2021 are presented (Fig. 3). In white cabbage, the significant time trends were negative in six areas, South Ostrobothnia, Häme, Uusimaa, South Savo, Satakunta, and Southwest Finland (Fig. 4). According to the model, the yield decreased by an average of 942–3070 kg ha^{-1} per year in these areas. Only in North Savo did modelling reveal an increasing trend (+2070 kg ha^{-1} per year), which was based, however, on very few observations (not shown in Fig. 4).

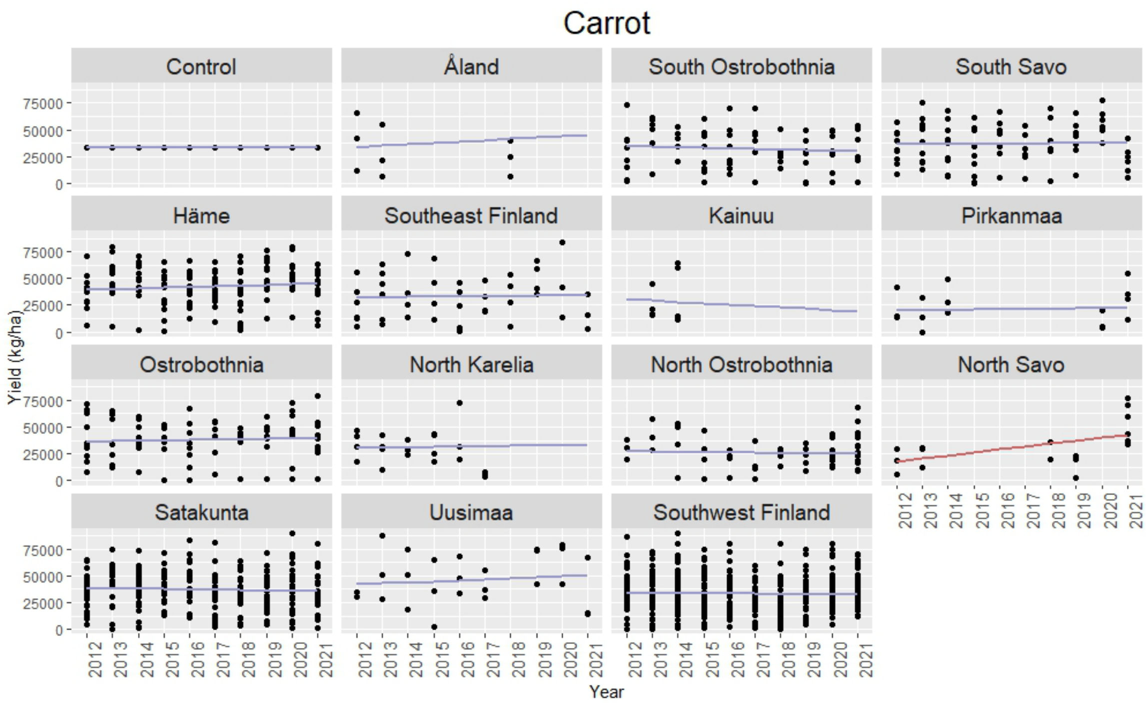

Fig. 2. Carrot yield (kg ha^{-1}) in different regions and years. Each point represents the yield of one farm. The lines correspond to the Bayesian model fit: red lines are considered significant (slope probability exceeds 95%), and blue lines are considered nonsignificant. Year–region combinations with less than three observations are omitted from the figure.

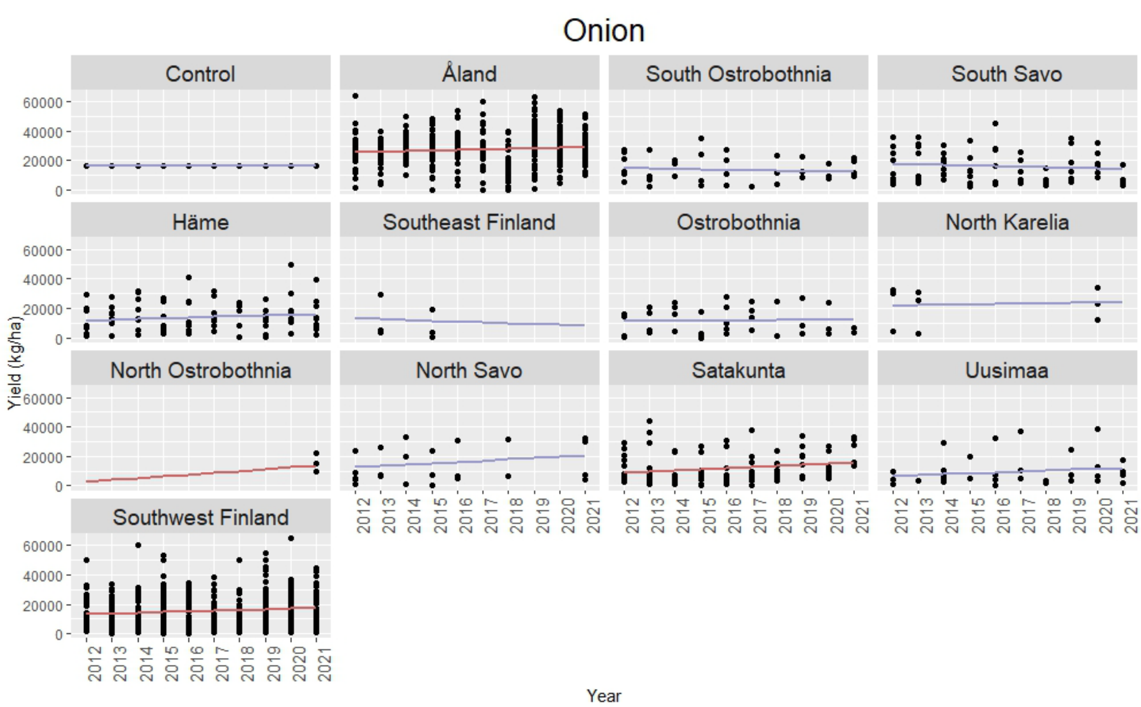

Fig. 3. Onion yield (kg ha^{-1}) in different regions and years. Each point represents the yield of one farm. The lines correspond to the Bayesian model fit: red lines are considered significant (slope probability exceeds 95%), and blue lines are considered nonsignificant. Year–region combinations with less than three observations are omitted from the figure.

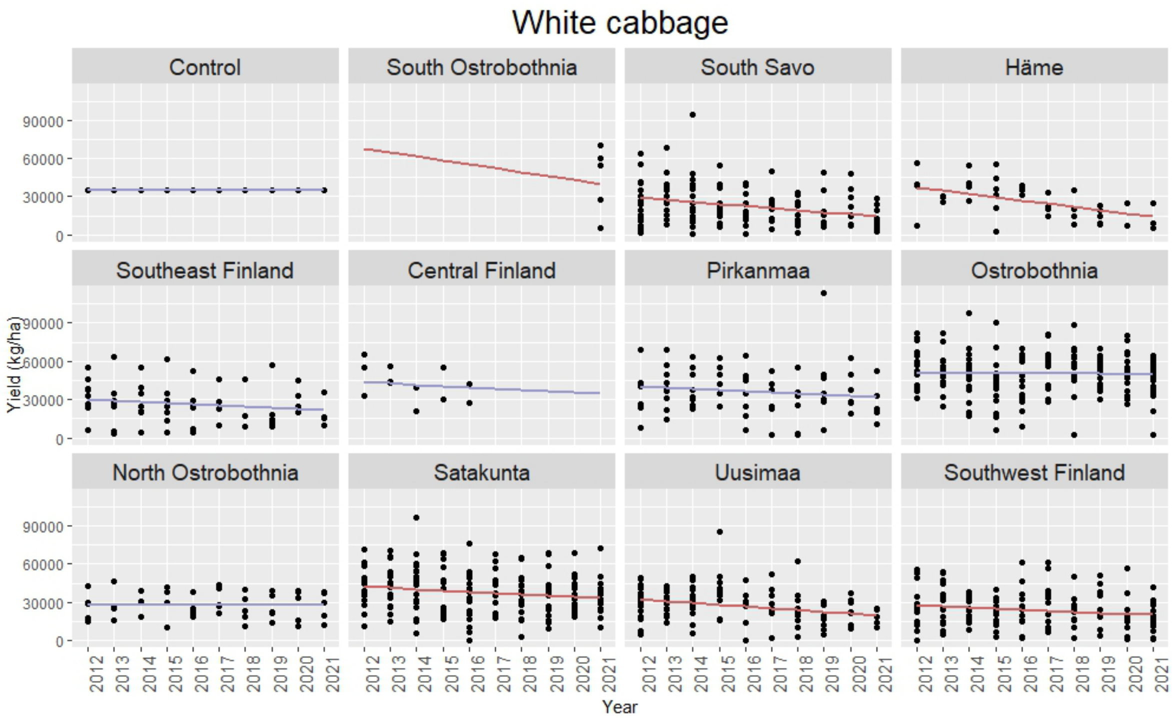

Fig. 4. White cabbage yield (kg ha^{-1}) in different regions and years. Each point represents the yield of one farm. The lines correspond to the Bayesian model fit: red lines are considered significant (slope probability exceeds 95%), and blue lines are considered nonsignificant. Year–region combinations with less than three observations are omitted from the figure.

Regional variation in yield

Regional variation in yield can be interpreted in addition to different regional time trends with the intercept values of the Bayesian models (Table 3). The higher the value for the intercept probability is, the higher the probability that the intercept term for a specific area will differ from the control baseline value, and the average yield is thus lower or higher than in the control region (in 2012).

In carrot, the yield was higher than the average in Satakunta and Häme (+5270 and +6200 kg ha^{-1}), which are among the three most important cultivation regions. North Savo, Pirkanmaa, and Lapland showed significant negative intercept values, meaning a lower (–10800 – –15300 kg ha^{-1}) than baseline yield in these regions. In other regions, average yields were not significantly different from the control region.

In onion, the model revealed that the average yield in Åland (the second most important cultivation region for onion) was 8680 kg ha^{-1} higher than the control baseline value. Yields lower than the baseline were observed in North Ostrobothnia, Lapland, Uusimaa, Satakunta, Ostrobothnia, Häme (–4 950 – –14 100 kg ha^{-1}) and in Southwest Finland (–3 420 kg ha^{-1}), which has the highest cultivation area of onion.

In white cabbage, the yield was higher than the baseline in Ostrobothnia (+15 600 kg ha^{-1}), Satakunta (+6 850 kg ha^{-1}), both of which are among the three major growing regions for white cabbage, and in South Ostrobothnia (+32 100 kg ha^{-1}), where only a few cabbage farms exist. A significant negative intercept, indicating a yield lower than the baseline, was found in North Savo, Lapland, North Ostrobothnia, South Savo, Southwest Finland, and Southeast Finland (–5 770 – –24 000 kg ha^{-1}).

Table 3. Model parameter mode estimates. Intercept and slope probabilities are calculated as the largest tail probability compared to zero from the posterior distribution (see Appendix). That is, the intercept and slope parameters can differ significantly from zero either negatively or positively, and the corresponding probability is reported. Intercept and slope values with probabilities exceeding 95% are marked with an asterisk. Intercept = mode value of the posterior distribution for the intercept term with respect to a specific region, intercept probability = tail probability for the intercept term for the specific region differing from the Control baseline, slope = mode value of the posterior distribution for the slope term with respect to a specific region, and slope probability = tail probability for the slope term for a specific ELY differing from the slope term for Control.

Region (ELY Centre)	Average cultivation area in the region in 2012–2021 (ha year^{-1})	Intercept	Intercept probability (%)	Slope	Slope probability (%)
			CARROT		
Control		33200		0	
Åland	3	437	52.2	1320	81.3
Southwest Finland	530	1060	76.8	–225	78.0
Uusimaa	6	8720	86.9	919	72.1
Southeast Finland	19	–1090	57	241	63.3
Satakunta	372	5270*	99.8	–335	83.1
Pirkanmaa	18	–13200*	98.5	266	61.5
Häme	382	6200*	98.8	630	88.4
South Savo	90	2980	78.6	158	57.7
Ostrobothnia	62	3280	81.4	355	66.6
South Ostrobothnia	47	1590	67.9	–579	79.3
Central Finland	5	–5070	82.8	–1320	88.1
North Savo	12	–15300*	99.8	2780*	99.8
North Karelia	10	–2740	72.7	308	63.4
North Ostrobothnia	30	–6050	92	–270	64.2
Kainuu	13	–2630	67.7	–1250	79.6
Lapland	4	–10800*	99.9	641	85.0
			ONION		
Control		16700		0	
Åland	241	8680*	> 99.9	421*	98.7
Southwest Finland	463	–3420*	> 99.9	479*	99.8
Uusimaa	7	–10100*	99.9	622	86.2
Southeast Finland	3	–3430	74.5	–558	59.8
Satakunta	53	–7480*	> 99.9	708*	97.3
Pirkanmaa	8	–16400	83.5	1840	79.3
Häme	39	–4950*	99.1	502	89.9
South Savo	23	1210	73.2	–434	82.7
Ostrobothnia	8	–5430*	96.5	106	57.1
South Ostrobothnia	62	–1960	80.2	–296	72.3
Central Finland	1	–17500	84.5	2060	73.6
North Savo	231	–4080	86.9	888	87.4
North Karelia	8	5180	90.8	279	64.5
North Ostrobothnia	2	–14100*	> 99.9	1240*	98.8
Lapland	1	–12800*	97.6	1940	90.6

			WHITE CABBAGE		
Control		35500		0	
Åland	1	–30800	89.4	5400	83.5
Southwest Finland	35	–7910*	> 99.9	–821*	98.4
Uusimaa	71	–2990	91.4	–1410*	99.8
Southeast Finland	16	–5770*	96.9	–833	88.2
Satakunta	133	6850*	99.8	–942*	98.5
Pirkanmaa	27	4440	88.8	–873	88.1
Häme	12	1680	69.4	–2550*	> 99.9
South Savo	44	–6180*	99.7	–1650*	> 99.9
Ostrobothnia	146	15600*	> 99.9	–133	62.9
South Ostrobothnia	8	32100*	99.6	–3070*	96.8
Central Finland	8	8200	92.8	–1010	82.6
North Savo	6	–24000*	> 99.9	2070*	99.1
North Karelia	3	–617	54.7	286	56.7
North Ostrobothnia	30	–7380*	99.7	–19.7	55.5
Kainuu	2	–8550	83.4	–922	70.5
Lapland	3	–11400*	99.8	1170	93.7

Yield gaps

Yield gaps were calculated for the three main production regions in each crop. Figure 5 shows that the potential yield (defined as the annual mean for the highest yielding 10% of farms per region) remained quite similar over the 2012–2021 period, as the analysis of general time trends above also showed. In white cabbage, some decrease was observed in potential yield, especially in the Uusimaa region.

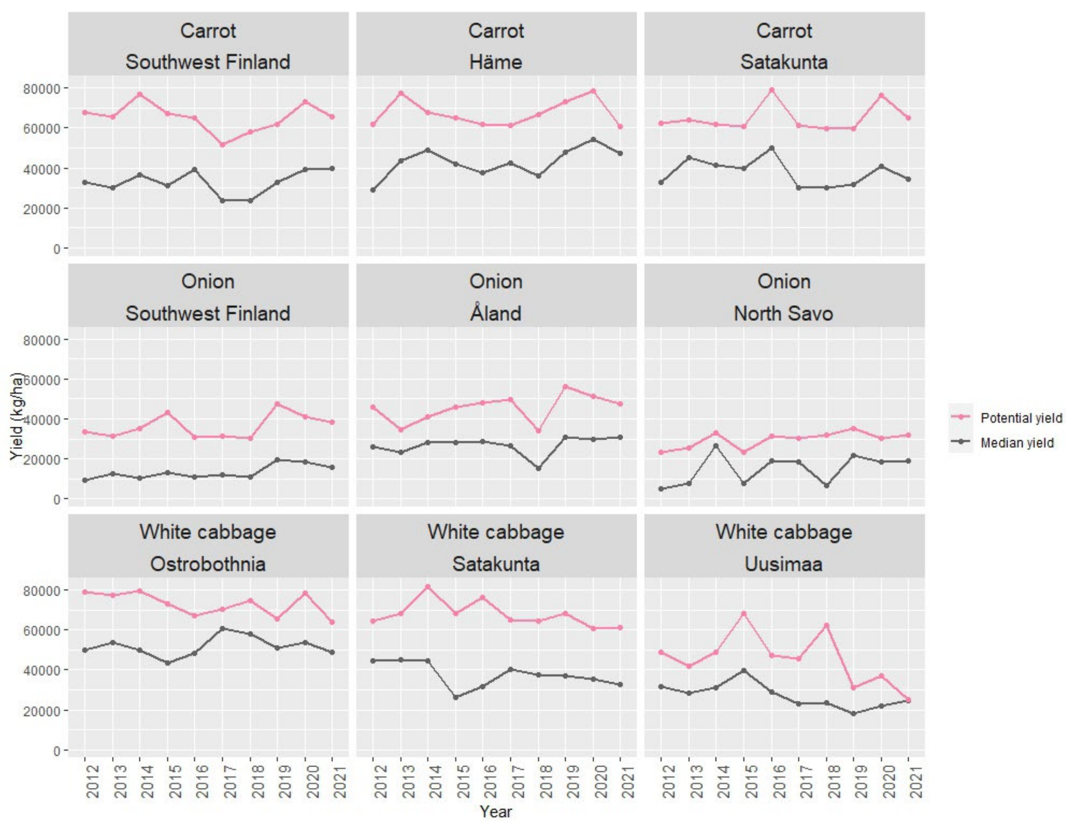

Fig. 5. Potential and median yield of carrot, onion, and white cabbage in the main production regions in 2012–2021.

The average proportion of yield gap (as a percentage of potential yield) was highest in onion and lowest in white cabbage, but differences were found between the regions (Table 4). However, the economic value of the yield gap was largest in carrot and lowest in onion.

Table 4. Average yield gap (% of potential yield) and its economic value (€ ha^{-1}) in the main production regions in 2012–2021. Economic value is calculated by the annual product prices obtained from Kasvistieto Ltd.

Plant	Region	Yield gap (% of potential yield)	Value of yield gap (€ ha^{-1})
Carrot	Southwest Finland	50	23456
	Häme	36	17869
	Satakunta	42	20133
	Mean	**43**	**20486**
Onion	Southwest Finland	63	15891
	Åland	41	13090
	North Savo	51	10324
	Mean	**52**	**13102**
White cabbage	Pohjanmaa	29	12890
	Satakunta	44	18800
	Uusimaa	38	11397
	Mean	**37**	**14362**

Discussion

Time trends in yield

During the 2012–2021 period, no general yield trends in vegetables were observed, but the trends varied between plant species and regions. In carrot, the yield trends were mostly not statistically significant in different regions, and the yield level tended to remain similar over the period. In onion, increasing statistically significant yield trends were found in some regions. In contrast, white cabbage had a significant negative yield trend within the most important production areas, indicating decreasing yields.

We have no data to analyse the causes of the varying yield trends in different vegetables over the 10-year period. Potopová et al. (2016, 2017) analysed the temporal trends of field-grown vegetables in Elbe lowland in the Czech Republic in 1989–2014. In majority of the crops the yields increased in the course of time, but not in savoy cabbage, root parsley, peas and cauliflower. When analysing the relation of weather conditions to the yield variability, Potopová et al. (2017) found that different weather variables were predominant in different crops.

In Finland, a similar declining trend as in cabbage yield in our survey has been observed in potato and rapeseed yields in the study by Peltonen-Sainio et al. (2016), which analysed the yield trends in 1970–2013. In northern growing conditions, yields tend to fluctuate between years, due to variable weather conditions and depending on crop species (Peltonen-Sainio et al. 2015a). White cabbage requires the highest nutrient (Salo 1999) and water (Koivisto and Salo 2021) supply of the studied species and carries a high risk of pest damage.

Peltonen-Sainio et al. (2015a) proposed that reduced N use might be one reason for stagnation or decline in cereal yields with other changes in agricultural practices driven by changes in prices and farm subsidies. In vegetable production, nitrogen fertilisation is limited by legislation (government decree 1250/2014) and until 2022, by the maximum fertilisation limits in the agri-environmental programme in which most farms participated. However, there have been no major changes in fertilisation limitations during the period under study, and no data on the nutrient application rates on vegetable production are available. The prices of fertilizers have increased about 20% during the 2012–2021 period, which might have affected the use of fertilizers (Statistics Finland 2024). However, it is not possible to estimate whether the declining yield trend of cabbage is related to insufficient nutrient supply.

Development of new cultivars aims to improve the yields, and the introduction of new vegetable cultivars may also affect the yield trends. We have no official data on the vegetable cultivars used in Finland, but it may be estimated that there have been no major changes in the cultivar selection during the 10-year period under study. However, as the length of the growing season increases, the cultivars requiring longer growing period and often having higher yields are likely to become more commonly used which offers potential for positive yield development in future.

Regional differences

Our analysis revealed significant regional differences in average yields. This is assumed to be partly related to different climatic and edaphic conditions during the growing season. In addition, production systems and farm specialisation differ between the areas. For example, early production of carrots and onions is common in Southwest Finland, and early cultivars' lower yield per hectare probably influenced the average yield in that region. Contract production for the freezing industry is mainly located in Satakunta and Southwest Finland. In that production system, farmers do not usually store the yield for long, and postharvest losses are therefore smaller than in yields that are stored long-term for the fresh market. This is a likely reason for the above-average carrot and cabbage yields in Satakunta.

Farmer's experience and active farm development also play an important role in the success of production (Koivisto et al. 2019), which may also be reflected in the regional differences found in our study, especially in the main production regions like Åland for onion and Ostrobothia for cabbage, which had higher than average yields and smaller yield gaps than the other main production regions of these crops. In regions with yields significantly lower than average, the number of farms producing the species under study was usually quite low.

Yield gap

Our study is the first to identify the magnitude of yield gaps in vegetable production in Northern Europe. The results cannot be directly compared with those of other studies due to the different methods of estimating potential and actual yields. Schils et al. (2018) reported that yield gaps of wheat and barley were 40–60% in southern Finland, which are of the same magnitude as the yield gaps estimated in our study.

We also estimated the economic value of the yield gap based on annual average prices. This value must be interpreted as a relative variable, not as a direct measure of economic loss, as prices tend to reflect supply. However, economic calculations indicate that in crops with a high potential yield like carrot, the value of yield loss can be very high.

Production structure

According to the statistics, Finland's open field vegetable production is dualistic: most of the yield for market is produced on the large professional farms included in our study. The average cultivation area per farm in our data in 2021 was 11.4, 9.0, and 5.9 ha for carrot, onion, and white cabbage, respectively, which was 23, 28, and 46% larger than the average cultivation area in 2012. Jaakkonen and Koivisto (2023) reported that horticultural production was increasingly centred on large farms: e.g. the ten largest farms produced 58% of the total onion yield and 46% of the total carrot yield in 2022. However, many farms have a very small cultivation area and a low or zero reported yield. For example, our original data contained an average of 355 farms per year producing onion, and only 41% of the farms fulfilled the criteria for professional farms used in our survey. On the other hand, professional farms corresponded to 97% of the total onion cultivation area. Carrot and white cabbage have a similar production structure, but the proportion of professional growers is larger in white cabbage (Table 2).

The group of farms producing vegetables but not selected for our survey based on our filtering criteria is assumed to have various professional backgrounds: they may include small horticultural farms with very versatile crop assortment in production, larger horticultural or agricultural farms with other species as major crops, and several farms growing vegetables for their own household use (which must be reported when grown on fields receiving farming subsidies). Organic farms were not included in the data of our survey due to the typically lower yields in organic production and the small cultivation area of organic vegetables in Finland. In 2021, the organic cultivation area of carrot, onion, and white cabbage was only 4.6, 2.2, and 4.2% of the total cultivation area of these species respectively, and they produced 3.3, 1.1, and 3.9% of the total yield of these species in Finland according to Horticultural Statistics.

Enlarging farm size and specialisation have many advantages related to the farm economy. However, when considering regional food production and food security, small farms may also play an important role in the future (Rivera et al. 2020, Ortiz-Miranda et al. 2022). Crop diversification can also significantly reduce the variability in yield (Paut et al. 2019); hence, a proper combination of specialisation and crop diversity is needed to control yield variability on the large farms that produce the largest share of vegetables for market.

The data used in our study, originating from official Horticultural Statistics, are based on farmers' own estimates, which are given in the late autumn each year. At that time, part of the yield is still in storage, and farmers need to estimate the marketable share of their yield. Different growers probably make their estimates with varying accuracy, but we can hypothesise that most growers have established methods for assessing yield quantity. Based on the high coverage of the data in the Horticultural Statistics, our analysis gives a clear view of the production structure and yield development of open-field vegetable production.

The analysis showed that there are many data points in which the yield per hectare is very low. These very low yield results may be due to severe damage caused by unfavourable weather (e.g. heavy rains or hailstorm), pest attacks or challenges in marketing the yield. In some cases, they may originate from inaccuracy in yield estimation or reporting in the annual yield survey.

How can production be improved?

Our analysis revealed that no general increasing trend in vegetable yields was observed during the 10-year study period, but the results varied between plant species and regions. We have no research data on the factors causing yield variation in vegetable production, and these need to be analysed more deeply. To ensure the profitability and sustainability of production and to improve the efficiency of input use, it is necessary to focus on reducing the yield variation between years and regions and reduce the yield gaps. This requires more efforts on measures to adapt to climate change and control the risks occurring during the cultivation. Bisbis et al. (2018) listed three main climate change adaptation strategies for outdoor vegetable production: integrated water management; adaptation strategies to heat stress (e.g. breeding heat and drought tolerant varieties); and adaptation to increasing infestation of weeds, pests, and diseases. With the aid of improved adaptation, it may be possible to produce higher yields of better external quality, thus reducing risks and waste and improving the economy of the sector (Bisbis et al. 2018).

Conclusions

No general increasing or decreasing trend was found in vegetable yield levels over the evaluated period. Onion production showed some increasing trend, while white cabbage had even a decreasing yield trend. There are regional differences in yield trends and average yields, which are likely to be caused by climate conditions but also by differences in farm specialisation and different markets. A yield gap analysis shows that there is potential for a significant increase in yields and returns in the main production regions. This will require more effort to control biological and other production risks.

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