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Impact of changing weather on the crops yield stability in different cropping systems

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Abstract. Changes in weather conditions make it possible to change the schedule of agricultural works and introduce new crops and crop rotations in Northern Europe. It is important that the yield of the crops in the rotation are stable under highly variable weather conditions, which would ensure a high total yield for the rotation. One of the goals of this long-term field experiment (2008–2022) was to study the effect of weather conditions on the total yield and stability in the crop rotation; crops of the given crop rotation were grown in organic and conventional cropping systems.

Compared to the pre-experimental period 1964–2007, the annual average air temperature of the test period 2008–2022 was higher by 1.1 degrees, whereas the increase in the annual average temperature was primarily due to the increase in winter and June–July temperatures. In the 3rd cropping cycle (2018–2022) the total yield of crop rotation as an average of fertilizer variants and experimental years was 21% and 24% lower than in the 1st (2008–2012) and 2nd (2013–2017) cropping cycles, respectively, which was mainly caused by the decrease in field pea yield. The effect of weather on yield stability was greatest for field pea. Fertilization with mineral fertilizers improved the stability of the total yield in the conventional cropping system. Correlation, factorial analyses of variance (ANOVA) and two-factor ANOVA were used to test the effect of cropping systems and climatic conditions on total and average DM yield of crop rotation, also each crop's DM yield.

Despite the negative impact of the weather, most of the yield loss can be prevented or the damage can be eased by careful planning and detailed knowledge about the influence of different weather factors. Further investigation is required to determine the change in growing season length, sowing dates and harvesting to provide farmers more detailed tools to predict and plan their actions.

Key words: cereals, field pea, potatoes, climate change, crop rotation, yield stability.

INTRODUCTION

Global climate change occurrence and its predicted continuation in the near future is currently widely accepted (Cook et al., 2016; Grusson et al., 2021). Alcamo et al. (2007) found that a warming trend (+0.9 °C) was established in Europe between 1901 and 2005. The warming climate has increased the frequency, intensity, and duration of heatwaves all over Europe (Lorenz et al., 2019). These climate change factors have important effects on the production of crops, on their yield, quality and stability (Zhao et al., 2022). The prevailing weather during the formation of the yield structure elements have a significant effect on the level of crops yield. The main structure elements of crop yield are number of productive tillers per plant, amount, and weight of grains in ear or amount and mass of potato tubers per plant (Evans, 1993; Ewert & Honermeier, 1999; Alaru et al., 2009). Therefore, weather conditions (air temperature and amount of precipitation) are important in the stage of plant tillering and grain filling or in the period of potato tuber formation, which in Estonian conditions is in June and July for spring crops.

Long-term field experiments allow studying the effect of changing weather conditions, also the effect of different cropping systems (organic and conventional production system) on yield level and stability. The effect of organic and mineral fertilizers on the crops yield level has been widely investigated (De Ponti et al., 2012). However, there is little information on whether yield stability of organic farming differs from that of conventional farming (Knapp & van der Heijden, 2018).

The yield stability (i.e., the variability of yield across years) has often been assessed by the coefficient of variation (CV; standard deviation divided by the mean yield over the same period) (Tilman et al., 2006; García–Palacios, et al., 2018). Also, in this paper the CV has been used to estimate yield stability, although, there are lot of stability indices that have been proposed over the years with pros and cons (Döring & Reckling, 2018; Reckling et al., 2021).

Based on the results of a long-term field experiment in Estonia, the article covers the effect of weather and cropping systems on the yield and yield stability of different crops. We hypothesised that different cropping systems (CS) have different yield stability.

MATERIALS AND METHODS

Design of the field experiment

A crop rotation experiment was established in 2008 at Eerika field experiment site of the Estonian University of Life Sciences (58°21’53” N, 26°39’58” E) consisted of five field crops as follows: spring barley (*Hordeum vulgare* L.) undersown (us) with red clover - red clover (*Trifolium pratense* L.) - winter wheat (*Triticum aestivum* L.*)* - field pea (*Pisum sativum* L.) - potato (*Solanum tuberosum* L.) (Fig. 1; Supplementary Table 1). One of the aims of the experiment was to study the effect of organic and conventional cropping systems on the yield and yield stability of field crops in a long-term field experiment. Detailed description of the experiment has been previously described by Alaru et al., 2014 and Keres et al., 2020. The soil type of the test field is Stagnic Luvisol (Deckers et al., 2002; WRB 2015), (sandy loam surface texture, C 1.38%, and N 0.13%, pH 6.0). The field experiment has a systematic block design with four replicates that include the following treatments: organic fertilisation and mineral fertilisation. The article covers three rotations of five cultivar crop rotation (first crop cycle period 2008–2012, second 2013–2017 and third 2018–2022).

The mineral fertilisation in conventional system was further divided into four subplots (10×6 m) (Fig. 1) corresponding to the mineral fertilizer (ammonium nitrate) rates used (N0, N1, N2, N3). The treatment N0 was the control treatment for the conventional system, without mineral fertilizers, but with pesticides. In other three conventional treatments the mineral nitrogen fertilizer NH_4NO_3 was applied once/or twice during growth (N1 = 40–50 kg N ha^{-1}; N2 = 80–100 kg N ha^{-1}; and N3 = 120–150 kg N ha^{-1}). Lower amounts of N were used for the barley us with red clover; red clover alone did not receive any mineral fertilizers. Field pea as a leguminous crop received mineral N at 20 kg N ha^{-1} in N1, N2 and N3 treatments. The conventional treatments N1, N2 and N3 had P (P_2O_5) and K (K_2O) fertilizers applied during sowing at the rate of 25 and 95 kg ha^{-1}, respectively (amounts of P and K were similar in all treatments) (Table 1).

Figure 1. 1) – photo of the experimental plots (Keres, 2022); 2) – map identification of the location of the experimental plots on the territory of Estonia (Google Maps, 2023).

Table 1. N,P and K applied in the conventinal crop cycle in NH_4NO_3 (2008–2022)

Crop rotation	Crop	N0 (kg ha^{-1})	N1 (kg ha^{-1})	N2 (kg ha^{-1})	N3 (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
I / 2008–2012	Barley + red clover	0	40	80	120	25	95
II / 2013–2017	Red clover	0	0	0	0	0	0
	Winter wheat	0	50	100	150	25	95
II / 2018–2022	Field pea	0	20	20	20	25	95
	Potato	0	50	100	150	25	95

The organic fertilization of three subplots in organic system was as follows: Org 0, Org I and Org II. The first organic treatment (Org 0) was a control of the organic system, without organic fertilizers. In the second organic treatment (Org I) cover crops were used as a green manure in winter: after winter wheat, potato and pea, mixture, or winter rye (*Secale cereale* L.) and winter oilseed rape (*Brassica napus ssp. oleifera var. biennis*) was used as a cover crop. Cover crops were ploughed into the soil as soon as possible after the snow melted in April. In the third organic treatment (Org II), fully composted cattle manure was added once during the first crop cycle, before potato. Manure, at the rate of 40 t ha^{-1} was ploughed into the soil to a depth of 20–23 cm in the autumn at the end of September or beginning of October before sowing of winter oilseed rape as the cover crop. In the second crop cycle period the application of manure was changed: the first application was in early spring before winter wheat regrowth at a rate of 10 t ha^{-1}, the second application before barley sowing at a rate of 10 t ha^{-1} and the third application before potato sowing at a rate of 20 t ha^{-1}. As the content of dry matter (DM) and nutrients in the composted cattle manure were variable, the N, P, K amounts applied with manure also varied. The total amount of N, P and K (kg ha^{-1}) applied in the first crop cycle period before potato was 165–179 kg ha^{-1}, 75–90 kg ha^{-1} and 130–145 kg ha^{-1} per cycle, respectively. During the second and third cycles, 44–54 kg ha^{-1}, 8–18 kg ha^{-1} and 17–43 kg ha^{-1} of nitrogen, phosphorus, and potassium, respectively, were given to wheat and barley. Same data for potato was 88–108 kg ha^{-1}, 16–32 kg ha^{-1} and 34–86 kg ha^{-1}, respectively (Table 2).

Table 2. N, P and K applied to the organic crop sycle in manure (2008–2022)

Crop rotation	Crop	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
I / 2008–2012	Potato	165–179	75–90	130–145
II / 2013–2017	Winter wheat	44–54	8–18	17–43
	Barley + red clover	44–54	8–18	17–43
	Potato	88–108	16–32	34–86
III / 2018–2022	Winter wheat	44–54	8–18	17–43
	Barley + red clover	44–54	8–18	17–43
	Potato	88–108	16–32	34–86

The tillage method in all treatments was mouldboard ploughing to a depth of 20–23 cm. The conventional systems were treated with several synthetic pesticides against weeds, diseases, and pests one to four times during growth period as required (Supplementary Table 2). In the organic systems, weed control after sowing and in the winter wheat field at the end of April was carried out by spring–tine harrowing. In all treatments, the red clover was crushed and ploughed into the soil in the middle to the end of August. Winter wheat, barley and pea were harvested with a Sampo harvester with header width of 2 m, i.e., the test area for grain yield calculation was 20 m^{2}.

Calculation of total yield per treatment

The total yield of each treatment represents the sum of the dry matter (hereinafter DM) yields of four crops treated with the same amount and type of fertilizer (i.e., 4 crops × 1 treatment × 4 replications). The biomass of red clover was excluded from the calculation of the total harvest, as it was ploughed into the soil.

Weather conditions

The climate conditions can be described as transition from marine to continental (Põiklik, 1986). The typical winter period (average air temperature permanently below 0 °C) lasts 115 days with an average air temperature of the coldest month −5.5 °C. The duration of the vegetation period (air temperature permanently above 5 °C) is 175–190 days. The period without night frosts is four months, and the warmest month is July, when the average air temperature is between 16–17 °C. Mean annual precipitation is 550–700 mm; average precipitation in the wettest months (April to the end of October) is 350–500 mm. (EMHI, 2020)

Meteorological data were collected from a meteorological station approximately 2 km from the trial site (Fig. 2, 3). The experimental period was divided into three sub-periods i.e., 1st (2008–2012), 2nd (2013–2017, and 3rd (2018–2022) based on the crop rotation. The base temperature for growing degree days (GDD) calculation was 5 °C.

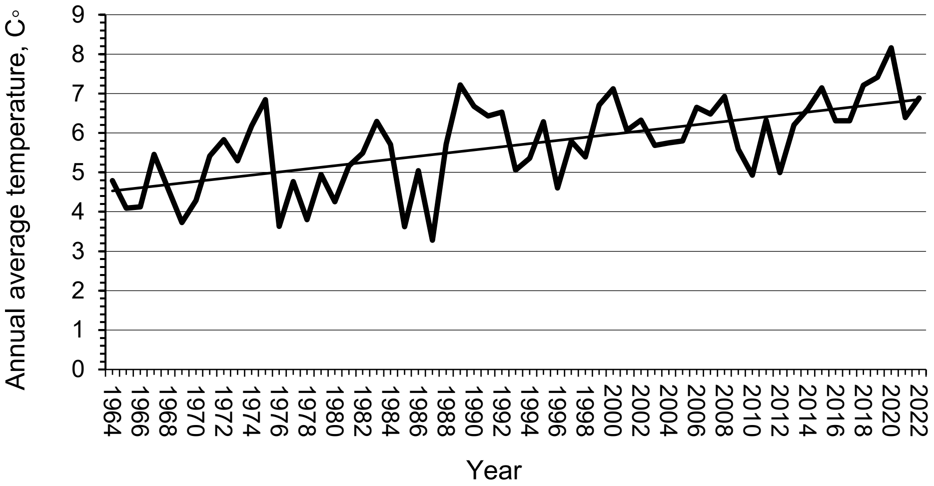

Figure 2. Annual average air temperature in the period 1964–2022.
$R^2 = 0.39, p < 0.01$.

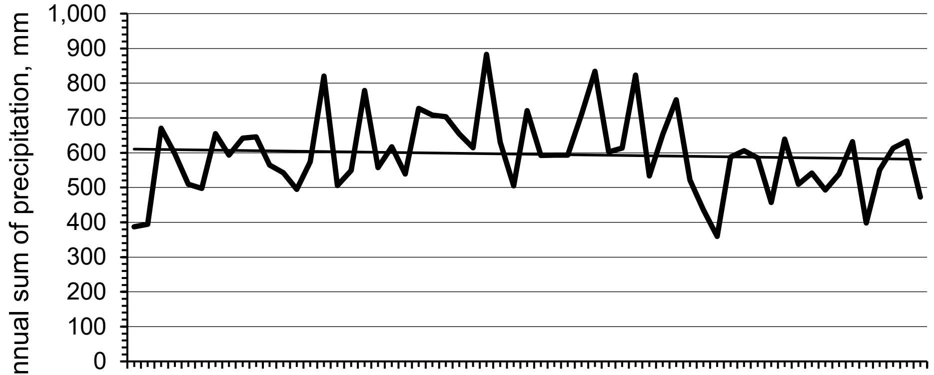

Figure 3. Annual sum of percipitation in the period 1964–2022.
R^2 =0 .006, $p > 0.05$

Statistics

Correlation, factorial analyses of variance (ANOVA) and two-factor ANOVA were used to test the effect of cropping systems and climatic conditions on total and average DM yield of crop rotation, also each crop's DM yield. The analysis considers two factors: cropping system (which consist of seven fertilizer application variants) and weather (temperature and precipitation data of the 15 years). The experiment included 7 fertilizer variants and five crops of four repetitions and the experiment has run for 15 years (three crop rotation periods). Total yield of crop rotation was calculated for four crops (red clover biomass value was not included in the calculation). Descriptive analysis and Fisher's least significant difference test for homogenous groups were used for testing significance differences between cropping systems, trial year and crop mean DM yields. The means are presented with their standard errors (±SE) (bars in the figures). The level of statistical significance was set at $p < 0.05$ if not indicated otherwise. The following formulas were used to calculate the proportional effects (%) of different factors:

$$Proportional\ effect\ for\ N\ treatments\ (\%) = \frac{Tr.SS}{TSS} \times 100$$

$$Proportional\ effect\ of\ trial\ year\ (\%) = \frac{YSS}{TSS} \times 100$$

where *Tr.SS* – treatment sum of squares, 7 terms; *YSS* – Year sum of squares, 15 terms; *TSS* – total sum of squares, 105 terms.

CV is calculated across years within each cropping system and within each crop both in conventional and organic cropping systems. CV was calculated using data of each crop, treatment, replication, and year. The 'year' parameter consists of the combined effect of the sum of precipitation and the average temperature of the corresponding year. The following formula was used to calculate the CV:

$$CV = \frac{SD}{MY} \times 100$$

where *CV* – coefficient of variation; *SD* – standard deviation; *MY* – mean yield for different crops in treatments and trial years.

RESULTS

Weather conditions during trial period

Meteorological data (1964–2022) collected from trial station revealed that the average annual air temperature has significantly increased ($R = 0.62$, $p < 0.01$; Fig. 2). The average annual air temperature in the period 1964–2022 varied from 3.3 °C (in 1986, followed by 3.6 °C in 1976) to 8.2 °C (in 2021, followed by 7.4 °C in 2019). Comparing the pre-experimental period 1964–2007 with the trial period 2008–2022, it turned out that the annual average air temperature of the last period has increased by 1.1 degrees, whereas the increase in the annual average temperature was primarily due to the increase in winter and June–July temperatures. The air temperature of the winter months from November to February increased by 1.5–2.1 degrees in the period of the 3rd crop cycle compared to the long-term average. Mean air temperature during growing period (in Estonian conditions from April to September) rose steadily from 1st to 3rd crop cycle (5.7–7.2 °C; Table 3). The same tendency applied to growing degree days (GDD).

The average annual GDD varied in 1964–2022 from 1,232 °C (in 1976, followed by 1,290 °C in 1978) to 2,068 °C (in 2018, followed by 1,820 °C in 2006). As the average annual air temperature was consistently higher during the experimental period compared to the pre-trial period, the same was true for the GDD indicators. Mean annual GDD value over years of 2008–2022 was 142 °C higher than that of period 1964–2007; during the plant growth period (April–September), the increase in the GDD value was mostly influenced by the rapid rise of temperature in June–July during the last crop cycle (2018–2022); the average GDD values of 1st, 2nd and 3rd crop cycles in June and July were 714 °C, 686 °C and 817 °C, respectively (Table 3).

Table 3. Average annual air temperature, GDD* and precipitation values over the years during the growing period from April to September in different cropping cycles**

Year	Month						Average/ Total
	April	May	June	July	August	September	
Average air temperature, °C							
2008–2012	6.0	11.5	14.7	18.6	16.1	11.6	13.1
2013–2017	5.0	12.2	15.1	17.3	16.7	12.0	13.1
2018–2022	5.9	11.6	18.0	18.7	17.7	12.1	14.0
1964–2022	5.0	11.3	15.5	17.4	16.1	11.0	12.7
1964–2007	4.8	11.2	15.3	17.1	15.9	10.8	12.5
Sum of precipitation, mm							
2008–2012	24	48	91	54	91	65	374
2013–2017	40	45	83	68	76	44	355
2018–2022	28	51	61	57	92	61	350
1964–2022	32	53	72	69	79	59	365
1964–2007	33	55	70	72	77	61	367
GDD, °C							
2008–2012	58	204	292	422	343	199	1518
2013–2017	42	230	304	382	362	211	1531
2018–2022	57	208	391	426	392	203	1677
1964–2022	50	200	314	386	344	183	1479
1964–2007	50	196	309	378	337	176	1445

*GDD – growing degree days; **growing period from April up to September in 1st (2008–2012); 2nd (2013–2017) and 3rd (2018–2022) crop cycle of five field crops.

The annual sum of precipitation during the period of 1964–2022 varied from 359 mm (in 2007, followed by 394 mm in 2018) to 883 mm (in 1990, followed by 835 mm in 1998; Fig. 3). Mean annual sum of precipitation in trial period (2008–2022) was 53 mm less than in the previous period (1964–2007). The yield and quality of plants was mainly affected by the amount of precipitation in June–July, also in August (harvest period of barley and field pea). The sum of precipitation of June and July in trial years was the lowest in the 3rd cycle –118 mm, which was 26–31 mm lower than previous cycles. However, due to the high variability between years within a crop cycle period, the differences between cycles were not significant (Table 3).

Influence of weather conditions on crops yield

The share of the influence of weather conditions and the cropping system on the total crop yield was similar, constituting 47% and 43% of the total effect of the experiment, respectively.

Of the tested crops grown in this crop rotation, only pea and potato yields were significantly affected by air temperature. The yield of potatoes was negatively correlated with the temperature in the period June–August, the high temperature in August has a particularly negative effect (formation of potato tubers; $R = -0.67$, $p < 0.01$). The pea yield was negatively affected by the higher temperature in June (period of formation of pea yield structural elements; $R = -0.56$, $p < 0.05$). For example, lower field pea yields were obtained in years when the temperature in June (pea pod flowering and pod formation) was 2.9–4.3 °C higher than the long-term average (Fig. 4). According to formula of linear trend line the yield of field pea in organic cropping system decreased steadily from the beginning to the end of field trial by 117 kg ha^{-1} in each year i.e., for 15 years up to 1,755 kg ha^{-1}. The same data for conventional system was 81 kg ha^{-1} and 1,215 kg ha^{-1}, respectively (Fig. 5).

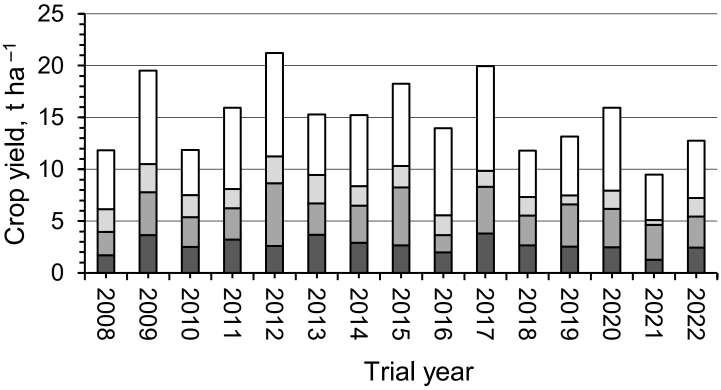

Figure 4. Average DM yield of treatments in different trial years. Different colours indicate different crops in the cropping system. White – potato; light grey – field pea; dark grey – Winter wheat; black – barley.

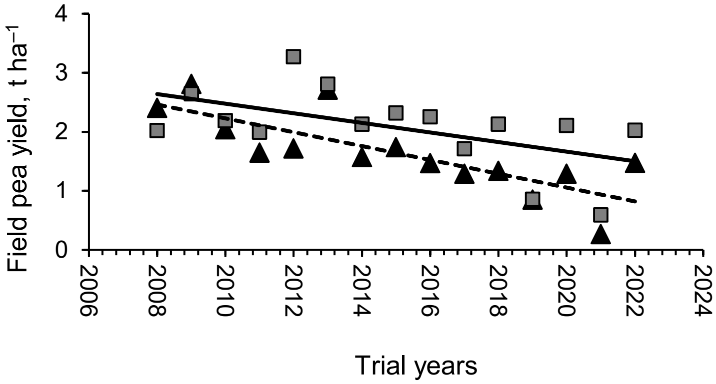

Figure 5. Field pea yield dynamics in organic and conventional systems in 2008–2022. Black triangle indicates organic and grey square indicates conventional cropping system. Dashed line indicates linear trendline in organic (org) cropping systems and solid line indicates linear trendline in conventional (conv) cropping systems. Y org = –0.1173x + 2.5788, R = 0.55, $p < 0.05$; Y conv = –0.0813x + 2.72, R = 0.54, $p < 0.05$, x[0, 15].

Total yield of the crops (barley us with red clover, winter wheat, field pea and potato) was not statistically different during the entire trial period due to the high variation (Fig. 6). In the 3rd cropping cycle the total yield of four crops was 1,2587 ± 1,045 kg ha^{-1}, which was 21% and 24% lower than in the 1st and 2nd cropping cycles, respectively. The decrease in total yield in the third rotation was mainly caused by the decrease in potato and field pea yield; the average field pea yield in 3rd crop rotation cycle was 1,286 ± 283 kg ha^{-1}, which was 35% and 42% less than that in the 1st and 2nd crop rotation cycle, respectively. The same data for potato was 5,616 ± 1,459 kg ha^{-1}, 24% and 28%, respectively.

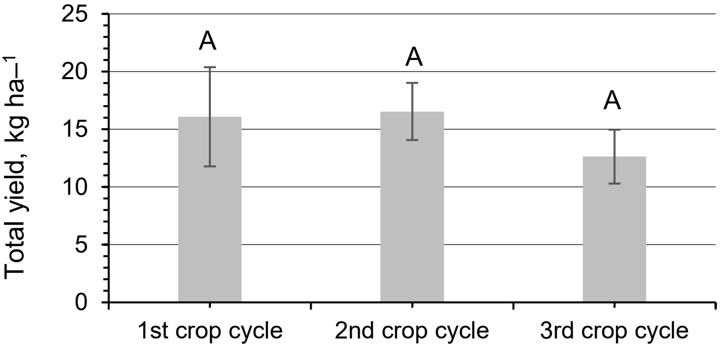

Figure 6. Total yield of four crops in the 1st, 2nd and 3rd crop cycles (i.e., 2008–2012, 2013–2017 and 2018–2022, respectively). *Different letters indicate a significant difference.

According to formula of linear trend line the total yield in organic and conventional cropping systems decreased significantly ($R = 0.28$, $p < 0.05$ and $R = 0.30$, $p < 0.01$, respectively; Fig. 7). According to the formula of the linear trend line, the total yield in the organic system decreased by 173 kg per year and in 15 years by 2,591 kg, i.e., by 19%. The same data for conventional system was 275 kg, 4,131 kg and 21%, respectively.

As said before, the influence of precipitation on crops yield level was not significant due to the large difference in rainfall distribution in the trial years.

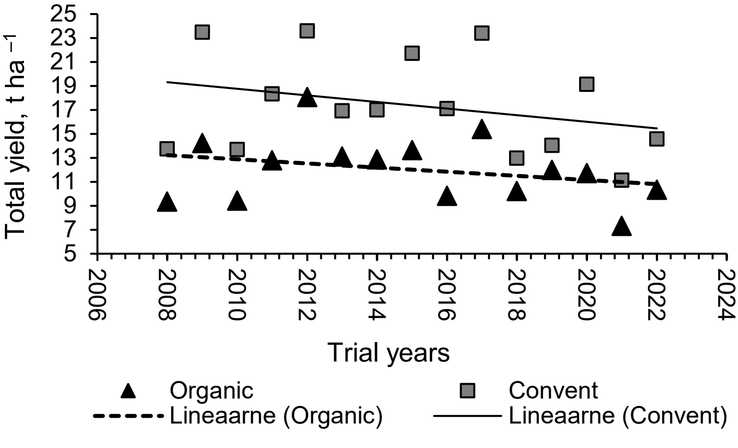

Figure 7. Dynamics of total yield in organic (org) and conventional (conv) systems in 2008–2022. Black triangle indicates yield in organic cropping system and grey square indicates yield in conventional cropping systems. $Y\ org = -0.1727x + 13{,}396$, $R = 0.28$, $p < 0.05$; $Y\ conv = -0.2754x + 19{,}588$, $R = 0.30, p < 0.01$, x[0, 15].

Influence of fertilisation regime on crops yield

For all crops, yields in organic system were significantly lower from the yields in the conventional system, up to 57% lower (barley us with red clover). The yield difference between organic and conventional systems was the smallest for field pea, with yield of organic plots up to 28% lower, followed by potatoes with 41% (Table 4).

Table 4. Crop yield (in DM, kg ha^{-1}) as an average over the trial years for different fertilization rates and total yield (t ha^{-1})

Treatment	Barley us with red clover (kg ha^{-1})	Winter wheat (kg ha^{-1})	Field pea (kg ha^{-1})	Potato (kg ha^{-1})	Total yield (kg ha^{-1})
Org 0**	1,764 ± 65b***	2,691 ± 131 b	1,633 ± 93 b	5,330 ± 266 b	11,418 ± 723 b
Org I	1,721 ± 73 b	2,876 ± 156 b	1,648 ± 97 b	5,602 ± 281 b	11,847 ± 784 b
Org II	2,047 ± 91 b	2,790 ± 169 b	1,608 ± 90 b	6,302 ± 210 b	12,747 ± 666 b
N0	1,966 ± 86 b	2,843 ± 150 b	1,702 ± 103 b	5,877 ± 254 b	12,388 ± 783 b
N1	3,499 ± 121 a	4,599 ± 202 a	2,237 ± 116 a	7,954 ± 316 a	18,289 ±1,022 a
N2	3,957 ± 153 a	4,773 ± 191 a	2,142 ± 103 a	8,504 ± 356 a	19,376 ±1,193 a
N3	3,792 ± 154 a	4,491 ± 224 a	2,135 ± 117 a	9,006 ± 456 a	19,424 ±1,439 a

*Barley us with red clover; **N1 = 40–50 kg N ha^{-1}, N2 = 80–100 kg N ha^{-1} and N3 = 120–150 kg N ha^{-1}; ***different letters in column denote significant difference.

Yield stability

The proportional effect of treatment (fertilization rate) and weather conditions on the yield of different crops is shown in Table 5. The weather had the greatest effect on the yield of field pea and fertilization with different nitrogen fertilizers had the greatest effect on the yield of winter wheat. Mean CV over experimental years and fertilization rates was highest for field pea and lowest for potato (Table 5). Yield stability between cropping systems differed significantly; stability for organic and conventional systems was 23% and 30%, respectively. However, mean CV over fertilized treatments of conventional system (without N0 treatment) did not significantly differ from that of the organic system (23% and 25%, respectively).

Table 5. The proportional effect (%) of different factors to yield variation and CV for the crops

Factor	Barley us with red clover	Winter wheat	Field pea	Potato
Year*	48	48	52	46
Treatment	25	31	10	25
CV	35	39	43	34

*Year–weather conditions in trial year; treatment – fertilization regime.

DISCUSSION

Estonian weather conditions are constantly changing and are challenging for agricultural producers to predict or plan their decisions ahead. Based on the measurements of the Estonian Environment Agency from 1960–1990, the average annual temperature in Estonia is 5.2 °C (EMHI, 2020). In Northern Europe lower temperature is a limiting factor for crop production (Holmer, 2008). From Fig. 2 we can see that the trend line of annual mean air temperature rose steadily from 1964 to 2022, which gives reason to believe that in the future it will be possible to grow those crops in Estonia, which until now were only grown in the south (Zhao et al., 2022).

The results of the experiment showed that the effect of the cropping system and the weather on the crop rotation total yield was considered equal, the effect of the weather constantly increasing. The yield level of field crop was primarily influenced by the temperature during the formation of yield structure elements (Van Dobben, 1962; Alaru et al., 2009). In Estonian conditions, the crop's yield structure elements of summer crops are formed in June (number of tillers and number of grains per spike) and July (grain mass); in the case of potatoes, the formation of tubers is mainly in July and the growth of tubers in August–September. In our experiment the yield of field pea and potato were negatively correlated with temperature in June and June–August, respectively and these crops are very sensitive to high temperatures and drought (Reckling et al., 2020; Mthembu et al., 2022), which probably shortened the pods and tubers filling period and reduced nutrient mobility and resulted in a significant reduction in yield. These results also correlate with an earlier publication by Van Dobben (1962), who showed that increased temperature shortens the time of production. The amount of precipitation did not affect the crops yield level in trial years due to the high variability of precipitation distribution during plants tillering, stem elongation and booting stages. For example, the amount of precipitation per month might be sufficient but if majority of precipitation occurs during a short period it has a negative effect on the yield. Also, in terms of yield precipitation during tillering, stem elongation and booting stage is more effective since the number of tillers and grains per spike is determine in these stages and water availability in grain filling stage will not compensate the lack of precipitation during the early stages of plant growth. Madhukar et al., 2022 also showed the negative correlation between yield and precipitation during the wheat earing stage.

The total yield of four crops was lowest in the 3rd crop cycle, which was caused primarily by decrease in potato and field pea yield. During the last ten years, there have been 2–3 heat wave periods mostly in June–July (air temperature above 30 °C during the growth period of plants), which coincided with a period of drought (Fig. 5, Table 3), which results with noticeable reduction in the total yield of crops in the third cropping cycle. The negative correlation between yield and temperature is also stated by Madhukar et al., 2022. Field pea yield decreased continuously during trial period, which may have been due to the continuous increase in temperature (Fig. 2). Similar results can be found in model-based research by Nendel et al., 2023 which showed decrease in soybean yield in increasing temperature. According to the formulas of linear trend line in Fig. 2 and 5, the calculated increase in air temperature by 0.6 °C during 2008–2022 caused a decrease in field pea yield during the same period by 1.76 t ha^{-1} in organic cropping system. The total yield of these crops depended mainly on the level of potato yield, because the share of the potato yield in the total yield was the largest (Fig. 4).

The second factor of this trial (cropping system i.e., availability of nitrogen from organic or mineral fertilizer) had the greatest influence on the winter wheat yield level, which is consistent with previous results (Table 5; Alaru et al., 2014; Keres et al., 2020). With the cooler weather in May, the tillering stage of winter wheat was extended, which promoted the formation of more shoots and ensured a higher yield, which is consistent with Soureshjani et al., 2019. Overwintering of wheat failed only once during these 15 trial years (winter 2015/2016), when the resowing with spring wheat was necessary. The limited availability of organic nitrogen in early stages of plants resulted significantly lower crop yield in organic production system, whereas the decrease of total yield in percentage was statistically equal in both systems (19% and 21%; Fig. 7) (Keres et al., 2020).

The field pea had the most unstable yield in this crop rotation (Table 5). These results are consistent with Reckling et al. (2020) results, who have found, that temperature correlated positively with instability of field pea yield and precipitation during specific period did not affect yield stability. The stability of the yield of winter wheat (CV was 39%) depended on the availability of nitrogen in spring in the stem elongation phase after wintering – during the yield structure elements formation. Earlier results from our long-term experiment show similar results (Alaru et al., 2014). The CV for barley (us with red clover) and potato were quite similar (35% and 34%, respectively; Table 5). For both crops in the cropping system the weather significantly influenced the yield. Barley inherently exhibits a higher level of abiotic stress tolerance than other crops (Wiegmann, 2019). Potato production is highly sensitive to water stress (Razzaghi et al., 2017) and in this experiment, low rainfall in July (potato flowering stage) significantly limited potato yield. Lynch et al., 1995 showed that a short period of water deficit during tuber initiation and flowering stage resulted in lower potato yield. Wagg et al., 2021 showed that water deficit results in delayed flowering which causes lower yield. On the other hand, higher potato yields (8.0–10.1 t ha^{-1} in DM) were obtained in years when September air temperature was higher than average (up to 1.8 °C), because this extended the potato growing season by 2–3 weeks.

Stability of total yield of crop rotation increased 5% by fertilization with mineral fertilizers in conventional crop system. Waqas et al., 2020 researched yield stability under different climatic conditions and stated that yield stability increases with balanced fertilisation. Average CV of all treatments in organic and conventional cropping system was 23% and 30%, respectively. Although the effect of plant protection products, especially fungicides was not studied, it might have had a yield stabilising effect in conventional cropping system since, previous studies have shown the positive effect of plant protection. (Mahmood et al., 2019)

Changing weather conditions urge researchers to conduct experiments to further understand the effect of different weather conditions on different aspects of the yield. To give more detailed explanations of the effect of weather further research is needed. Possible limitations of the study are connected to the open-air experiment and different uncontrollable variables regarding environmental factors. However, current study gives a good basis for further research. Possible areas to investigate are not only related to the yield of the crops but also the quality. Different types of crops not covered in this paper could also be included, as well as the influence of extreme weather events on the yield and yield stability of the crops.

CONCLUSIONS

Annual mean temperature in Estonia has increased by 1.1 °C from 1964 to 2022. The air temperature had significant effect on the yield of crops through affecting the formation of the elements of the crop yield structure. The effect of precipitation on yield was not significant, because the distribution of precipitation during the growing season was highly variable. The most unstable crop yield had field pea, followed by winter wheat and barley (CV was 43%, 39% and 35%, respectively). Fertilization with mineral fertilizers improved the stability of the total yield in the conventional cropping system.

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