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Long-term nitrogen and phosphorus balances for spring barley (*Hordeum vulgare* L.) cultivation as affected by primary tillage of a Nordic clay soil

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ABSTRACT

In conservation agriculture no-tillage and reduced tillage are used to increase the sustainability of cultivation. There is, however, a paucity of data on the long-term effects of no-tillage and reduced tillage management on the nutrient balances for grain production in a cool and humid climate. This information is relevant for evaluating the effects of primary tillage systems on environmental risks and nutrient input use efficiency of cultivation. In the current study, we examined the long-term effects of primary tillage methods on grain and nitrogen (N) and phosphorus (P) yields, and N and P balance for spring barley (*Hordeum vulgare* L.) cultivation on a Nordic clay soil (Vertic Endostagtic Cambisol) in 2000–2019. Three types of primary tillage were compared: mouldboard ploughing to 20–25 cm depth, stubble cultivation to 10–15 cm depth (later reduced tillage) and no-tillage. The trial was left without P fertilizer since 2008. Based on the current results, ploughing and reduced tillage were comparable primary tillage methods but no-tillage increased the N and P balances. Barley yield was 12–13% higher for ploughed and reduced tillage treatments than for no-tillage. N yield was 18% and 21% higher and P yield 12% higher with ploughed and reduced tillage compared with no-tillage, respectively. N balance was 43.6, 41.8 and 52.5 kg/ha with ploughing, reduced tillage and no-tillage and P balance was −5.9 kg/ha with ploughing and reduced tillage and −4.5 kg/ha with no-tillage, respectively.

1. Introduction

Increasing human population and climate change set new demands on agriculture (Hobbs et al., 2007; Michler et al., 2019; Malhi et al., 2021). In the future agriculture will need to produce more food from less land with a reduced impact on the environment (Hobbs et al., 2007; Calabi-Floody et al., 2018). One sustainable strategy to reach these goals is conservation agriculture where there are three principles: no-tillage/minimum soil disturbance, soil crop cover, and crop rotation where the target is to improve the physical, chemical and biological properties of soil, decrease wind and water erosion, and enhance crop growth (Hobbs et al., 2007; Palm et al., 2014; Giller et al., 2015; Choudhary et al., 2016; Kassam et al., 2018). Conservation agriculture was practised globally on about 14.7% of the total arable land in 2019 (Kassam et al., 2022). Also, the EU is setting demands for farmers: in the EU new agricultural policy (CAP, 2023–2027) every farm needs to have at least 33% crop cover during winter and there needs to be at least a 33% change in cultivated crops annually (CAP, 2023). The target of these demands is to guide farmers toward more sustainable agriculture (Turtola and Jaakkola, 1995; Puustinen et al., 2007; Cordell et al., 2009; Steele et al., 2012).

The results of the effects of different primary tillage methods on crop grain are variable. Some studies report higher crop yield with conventional tillage than with no-tillage (Gangwar et al., 2006; Van den Putte et al., 2010; Arvidsson et al., 2014; Adimassu et al., 2019), while also opposite crop response has been found (Govaerts et al., 2005; Li et al., 2007; Franchini et al., 2012; Sommer et al., 2012; Huang et al., 2018). One reason that could affect the results is that primary tillage methods affect soil properties such as soil water holding capacity and soil bulk density differently in different soil types (Kladivko, 2001; Singh et al., 2015). For example, heavy clay soils favour reduced tillage and no-tillage methods (Rasmussen, 1999), while Carter (1991) reported that with sandy loam soil there were no differences between primary tillage methods if weather conditions were optimal. Generally, growing seasons with high precipitation favour ploughing while growing seasons with low precipitation favour no-tillage methods (Carter, 1991; Pietola

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and Tanni, 2003; Wang et al., 2011; Huang et al., 2018; Omulo et al., 2022). Furthermore, with no-tillage, sowing can be delayed due to higher soil water content and slower drying compared with the case for tilled soil (Perez-Bidegain et al., 2007; Alvarez and Steinbach, 2009; Soane et al., 2012), which may also affect crop yield.

Crop nutrient uptake is one measure to be followed when analysing the impact of agriculture on the environment. It is also an indicator of crop nutrient input use efficiency. Like crop yield, also crop nutrient uptake can be influenced by primary tillage methods (Ishaq et al., 2001). However, the interaction between tillage method and crop nutrient uptake varies: Sieling and Kage (2006) did not establish a significant effect of tillage on crop nitrogen uptake but Ishaq et al. (2001) reported higher crop nitrogen, phosphorus and potassium uptake with conventional tillage than with minimum tillage. In the current study, we use the term 'crop nutrient uptake' when determining spring barley (*Hordeum vulgare* L.) nutrient yield harvested in grain.

Crop nutrient uptake is essential knowledge when counting nutrient balance (nutrientinput given as fertilizer, in seed and deposition, minus nutrient removal harvested in yield), which is used to indicate the potential risk of nutrient losses from field to the environment (EUROSTAT, 2020). In the current research, positive nutrient balance indicates nutrient surplus and negative indicate nutrient deficit. Turtola et al. (2017) and Uusitalo et al. (2015) reported that high nutrient balance of crop cultivation increases the risk of nutrient leaching. One way to decrease crop nutrient balance is to decrease the amount of fertilizer (Turtola et al., 2017) and secure crop grain by protecting against pests because a well-being crop can use the applied fertilizer more effectively (Delin et al., 2008; Kauppi et al., 2021). In addition to chemical control, crop rotation (Bullock, 1992; Bailey et al., 2001; Mamolos and Kalburtji, 2001) and tillage (Andersen, 1999; Bárberi and Cascio 2001; Murphy et al., 2006; Paulitz et al., 2010) represent potential ways to control pests and secure crop grain and nutrient yield.

Previous studies of different primary tillage systems in cereal crop production have focused mainly on the effects on grain yield and seldom on the nutrient yield or nutrient balance. The aim of the current study was to examine the long-term effects of different primary tillage methods on grain and nutrient yield, and nutrient balance for spring barley cultivation on a clay soil in Nordic conditions. This information is essential when evaluating the sustainability of primary tillage methods as a part of spring cereal cultivation under different conditions.

2. Materials and methods

A long-term field trial was established in Jokioinen, in southwest Finland (60°49′N, 23°28′E) in 2000. The data presented in this study were collected from 2000 to 2019. Before establishing the experiment, spring cereals were cultivated on the field according to conventional methods – primary tillage was mouldboard ploughing to a depth of 20–25 cm.

Field experiment was conducted on a clay soil. The mean clay content at 0−20 cm was 62% and at 20−40 cm 81% (Regina and Alakukku, 2010). The soil was classified as a Vertic Endostagtic Cambisol (IUSS Working Group WBR, 2006). The detailed physical and chemical properties of the soil at 0–20 cm were described by Regina and Alakukku (2010) and Palojärvi et al. (2020). For autumn-ploughed soil the mean soil organic matter content (SOC) was 2.70%, $pH_{water\ 1:2.5}$ was 6.3−6.5, and soil soluble reactive phosphorus content (extraction with 0.5 M acid ammonium acetate, pH 4.65, Vuorinen and Mäkitie 1955) was 18−19 mg/l soil.

2.1. The experimental design

The trial was conducted as a split plot design with four replicates. It was established in 2000 to examine three primary tillage treatments in autumn (main plot): mouldboard ploughing to 20−25 cm depth (CT), stubble cultivation (later reduced tillage) to 10−15 cm depth (RT), and no-tillage (NT). In 2001−2010, the subplot (split-plot, area $6\times40\ m^2$) treatment was the sowing method in spring: combined rotary harrowing and sowing (one pass method, combined drill: seed (shoe coulters)) and fertilizer placed at the same time in separate rows (row space of drilling coulter 12.5 cm); drill sowing with single disk coulters, seed and fertilizer placed in separate rows (row space of drilling coulters 12.5. cm), and direct drill sowing (double disk coulters, row space 14.5 cm), seed and fertilizer placed in the same row. During 2001–2010, the crop in the trial was spring barley, except in 2003 when it was spring oats (*Avena sativa* L.).

In 2011, the experimental design was changed by establishing two crop sequences to replace the previous subplots: Spring barley monoculture was continued, and a four-year crop rotation system was started: spring barley, faba bean (*Vicia faba* L.), spring oats, spring turnip rape (*Brassica rapa* L.). The varieties represented the commonly cultivated varieties in Finland and the spring barley varieties were all two-rowed. The four-year crop rotation was carried out twice during the trial period. From 2011, the subplot area was $9\times40\ m^2$. In this publication, we present the results of the primary tillage treatments in the barley monoculture plots 2000–2019.

2.2. Trial field management and weather conditions

During the trial period, the autumn tilled treatments were levelled in spring using a harrow to 3–5 cm depth 2–10 days before sowing to reduce evaporation. The depth of the seedbed prepared by a rotary harrow was about 5 cm. The crop was sown using a combined drill, placing the seeds (shoe coulters) and fertilizer at the same time in separate rows (row space of drilling coulter 12.5 cm and that of fertilizer coulters 25 cm). From 2011, no-tillage plots were sown with a direct drill (double disk coulters, row space 14.5 cm), seed and fertilizer placed in the same row. The target seeding rate with spring barley and oats was 500 viable seeds per square metre.

The sowing date ranged between the 2nd of May and 2nd of June, and it was mainly the same for different tillage methods (Table 1). However, the wet soil conditions in 2004, 2007, 2015, 2017 and 2019 delayed sowing of no-tillage treatments by 14, 3, 8, 5, and 3 days, respectively. The crop was harvested on the same day, except in 2004, when the no-tillage plots were harvested three weeks later than other treatments.

During the growing seasons, herbicide treatments were made at the two to three leaf stage at BBCH 12–14 (Bleiholder et al., 1997). Glyphosate was used annually, except in 2001, 2005, 2008, 2012, 2013 and 2017, according to the need to control couch grass (*Elymus repens* (L.). No fungicides or insecticides were applied during the trial period.

During 2000–2019, the annual dose of nitrogen (N) fertilizer for spring barley and oats was 90–100 kg/ha. For phosphorus (P) fertilizer, the amount varied between 8–20 kg/ha in 2000–2007 (Table 2). After 2008, no P fertilizer was applied as it was not necessary for spring barley based on the P content of soil.

2.3. Measurements and nutrient balance calculation

Grain was harvested with a combine harvester. Harvested area of a plot was $60\ m^2$ in 2000–2010 and $30–48\ m^2$ in 2011–2019. After harvesting, the grain was cleaned and the dry matter content of the grains from each plot was determined. The dry matter content of grain was determined by drying a subsample of 40 g at 105 °C overnight. Cereal yield results are presented at 14% moisture content.

The nitrogen content of the grain dry matter was measured using the Kjeldahl method and a Kjeltec Auto 1030 Analyzer (AOAC methods, 1980). For phosphorus, the dried samples were ashed at 450°C and then dissolved with 100 ml 0.2 M HCl. Phosphorus was determined colourimetrically with a modified ammonium-vanadate-molybdate method (Gericke and Kurmies, 1952). Nutrient yield harvested in grain was calculated using the harvested dry matter yield and dry matter nutrient

Table 1
Annual weather conditions during the growing seasons in 2000–2019 and the long-term average from May to September 1991–2020. The mean temperature, cumulative precipitation, effective temperature sum (≥ 5°C), sowing start date and harvesting end date are presented.

Year	Mean temperature °C	Cumulative precipitation. mm	Effective temperature sum °C	Sowing date	Harvesting date
2000	13.0	280	1048	9.5.	11.9.
2001	14.2	199	1882	9.5.	21.8.
2002	15.7	205	1071	2.5.	13.8.
2003	14.9	224	1008	28.5.	28.8.
2004	13.6	395	978	3.5.	6.9.
2005	14.2	305	986	10.5.	22.8.
2006	15.3	109	982	10.5.	14.8.
2007	15.4	232	1096	11.5.	23.8.
2008	12.6	278	1041	14.5.	15.9.
2009	15.0	213	1092	19.5.	7.9.
2010	17.6	199	1142	20.5.	24.8.
2011	15.6	297	1088	9.5.	16.8.
2012	12.8	258	1022	30.5.	21.9.
2013	16.2	188	1186	15.5.	28.8.
2014	15.3	231	1181	19.5.	3.9.
2015	12.8	261	1094	25.5.	28.9.
2016	14.4	245	1202	11.5.	9.9.
2017	11.9	384	1087	24.5.	19.10.
2018	16.4	193	1352	29.5.	24.9.
2019	14.7	282	1301	14.5.	18.9.
Long-term average 1991–2020	13.5	306	1301		

Table 2
Spring sown crops and crop varieties cultivated, amount of seeds and applied nitrogen (N) and phosphorus (P) doses (kg/ha) in fertilizer and seed in 2000–2019.

Year	Crop	Variety	Amount of seeds (kg/ha)	Fertilizer N	Fertilizer P	Seed N	Seed P
2000	Barley	Inari	245	90	18	4.07	0.84
2001	Barley	Saana	240	100	20	4.16	0.92
2002	Barley	Saana	280	90	14	4.86	0.96
2003	Oats	Roope	180	110	17	3.93	0.65
2004	Barley	Saana	265	90	14	3.67	0.80
2005	Barley	Saana	220	90	14	3.19	0.64
2006	Barley	Saana	190	90	14	2.96	0.55
2007	Barley	Saana	270	100	8	4.43	0.93
2008	Barley	Annabel	240	110	8	3.59	0.82
2009	Barley	Annabel	210	100	0	2.86	0.63
2010	Barley	Annabel	210	100	0	3.5	ND
2011	Barley	Annabel	260	100	0	4.48	1.0
2012	Barley	Annabel	190	90	0	2.8	0.65
2013	Barley	Harbinger	250	90	0	3.66	0.79
2014	Barley	Harbinger	230	90	0	3.66	0.81
2015	Barley	Harbinger	280	90	0	3.70	0.90
2016	Barley	Harbinger	200	90	0	2.58	0.65
2017	Barley	Harbinger	230	100	0	3.05	0.75
2018	Barley	Trekker	260	100	0	4.28	0.84
2019	Barley	Trekker	260	100	0	3.60	0.80

content. The nitrogen and phosphorus balances were calculated with FAOSTAT-protocol (FAO, 2023) by subtracting nutrient yield harvested in grain yield from the sum of the amount of nutrient inputs (nutrient given in fertilizer and seed) (Table 2) and annual deposition (3.0 kg N ha^{-1}; 0 kg P ha^{-1}). In the current research, the only source of fertilizer were mineral fertilizer and biological N fixation was not taken account as the target crop was spring barley.

$$N_{balance}\ (kg\ ha^{-1}) = (N_{fertilizer}\ (kg\ ha^{-1}) + N_{seed}\ (kg\ ha^{-1}) + 3.0\ (kg\ ha^{-1}\ N)) - N_{yield}\ (kg\ ha^{-1}) \quad 1)$$

$$P_{balance}\ (kg\ ha^{-1}) = (P_{fertilizer}\ (kg\ ha^{-1}) + P_{seed}\ (kg\ ha^{-1})) - P_{yield}\ (kg\ ha^{-1}) \quad (2)$$

.

2.4. Statistical analyses

Generalized linear mixed models (GLMM) were used for all dependent variables using the GLIMMIX procedure of the SAS Enterprise Guide 7.15 (SAS Institute Inc., Cary, NC, USA). The categorical variables of primary tillage treatment (ploughing, reduced tillage, no-tillage) and year, and their interaction were used as fixed effects. The amount of phosphorus fertilization, which varied during the study period, was used as a continuous covariate in the models (Supplementary Table 1). A Gaussian distribution was used for all dependent variables. The random effects used were block and block × year, explaining together 17–51% of total variation depending on the model. The used model for yield was:

$$y_{ijk} = \mu + block_i + tillage_j + year_k + P_{ijk} + block \times year_{ik} + tillage \times year_{jk} + \varepsilon_{ijk} \quad (3)$$

.

where y_{ijk} is the observed yield, μ is the intercept, $block_i$ is the effect of the i^{th} block, $tillage_j$ is the average yield level of the j^{th} tillage method, $year_k$ is the average yield level at the k^{th} year and P_{ijk} is the amount of phosphorus fertilizer used. The model also includes the interactions of year with block and tillage method, and ε_{ijk} is the normally distributed residual error.

Degrees of freedom of the models were calculated using the Kenward-Roger method. Tukey's method was used for pairwise comparisons of the estimated means for fixed effects at a significance level of $\alpha = 0.05$. The normality of residuals was studied through residual plots and was adequate for each model.

3. Results

3.1. Annual spring barley yields achieved with different tillage treatments

The average barley yield over the years and tillage treatments was 3860 kg/ha. The yield was lowest in 2015 with no-tillage (600 kg/ha) and highest in 2019 with reduced tillage (6300 kg/ha) (Fig. 1a).

In 2004 and 2017 the precipitation was clearly higher in the growing season (365 mm and 383 mm, respectively, Table 1) than the long-term average, and the barley yield was 2300 kg/ha and 1100 kg/ha higher in the ploughed and reduced tillage than in the no-tillage plots, respectively. In 2006, precipitation was low (109 mm) and with ploughed and reduced tillage plots the barley yield was approximately 700 kg/ha lower compared with no-tillage. In 2001, the seed was directly drilled too deep, which partly caused the 900 kg/ha yield reduction in no-tillage plots.

Over the years, 12.7% and 12.3% higher barley yields were achieved with ploughed and reduced tillage, respectively, compared with no-tillage (Fig. 2a). There was no statistically significant difference in barley yield between ploughed and reduced tillage treatments. The specific details of statistical analyses are presented in Supplementary material (Table A1-A3).

3.2. Effect of primary tillage on nutrient yields

The N and P yields from ploughed and reduced-tilled treatments were significantly higher than those from no-till treatment (Fig. 2b, e). It was estimated that nitrogen yield was 17.5% and 21.1% higher with ploughed and reduced tillage, respectively, compared with no-tillage. N yield with ploughed was 60 kg/ha, with reduced tillage 62 kg/ha and with no-tillage 51 kg/ha. Similarly with P, yield with ploughed and reduced tillage was 13 kg/ha and with no-tillage 12 kg/ha. Annual N and P yield harvested in grain and the N and P content of grain are presented as supplementary material (Fig. 1). The estimated mean N content of the grain was 1.7% and 1.8% for ploughed and reduced tillage treatments, respectively, and 1.6% for no-tillage (Fig. 2d). The no-tillage treatment reduced both grain yield and the N content of grains (Fig. 2a, d).

The phosphorus yield was estimated to be 12.4% higher with ploughed and reduced tillage compared with no-tillage (Fig. 2b). Primary tillage did not have a statistically significant effect on the P content of grain yield. The estimated mean P content of the grain was 0.37% for all tillage treatments. Also, there were no significant differences between ploughed and reduced tillage treatments for N and P yields.

3.3. Effect of primary tillage on nutrient balance

Annual N and P balance of crop cultivation is presented in Figs. 1b and 1c. Annual N and P yield harvested in grain yield and the N and P content of grain are presented in supplementary material (Fig. 1). Annual variation in N and P balance correlated negatively with grain yield. The use of P fertilizer had no statistically significant effect on barley yield, nutrient yield or nutrient balance even though the trial received no P fertilizer since 2008 (Supplementary material, Table 1).

There were clear differences among primary tillage methods in the nutrient balance for spring barley cultivation (Fig. 2c, f). With ploughed and reduced tillage, it was estimated that the nitrogen balance was 16.9% and 20.3% lower compared with no-tillage, respectively. Similarly, with phosphorus balance, ploughed and reduced tillage were estimated to be approximately 32% lower compared with no-tillage. However, there were no significant differences between ploughed and reduced tillage for N and P balance.

4. Discussion

We examined the long-term effects of three primary tillage methods on a Nordic clay soil, autumn ploughing, reduced tillage, and no-tillage, on spring barley grain, N and P yields, and the N and P balance. To our knowledge, this is the first long-term study in which the effect of primary tillage on nutrient yields and balances has been reported for Nordic conditions. The knowledge of the nutrient balances is relevant when the potential risk of nutrient losses from field to environment is evaluated (Uusitalo et al., 2015; Turtola et al., 2017; EUROSTAT2020). Based on this, we can estimate the efficiency of the use of N and P inputs in cultivation. P balance is also used to predict the change in soil test P concentrations over time, allowing projection of agronomic benefits and environmental risks for different P use strategies (Uusitalo et al., 2016).

4.1. Long-term effects of primary tillage on spring barley yield

According to our results on a heavy clay soil, barley yield was increased with ploughing and reduced tillage compared with no-tillage. With both tilled treatments barley yield averaged about 4000 kg/ha, while with no-tillage barley yield averaged about 3600 kg/ha, being lower than the average barley yield of 3800 kg/ha in Finland in 2022 (Luke, 2022). Similar results were also reported by Arvidsson et al. (2014) with spring cereals, and Van den Putte et al. (2010) and Townsend et al. (2016). However, also contrasting results were reported for winter wheat (*Triticum aestivum* L.) on a heavy clay soil in sub-tropical conditions (Li et al., 2007) and semi-arid conditions with spring wheat and maize (*Zea mays* L.) (Govaerts et al., 2005; Sommer et al., 2012).

The variation in yield response among primary tillage treatments in different studies is expected. Reducing the primary tillage depth and intensity changes the physical, chemical and biological properties of the topsoil (previous primary tillage depth) (Logan et al., 1991, Schjø2013). The effect of changes in soil properties on crop yields varies according to soil type (e.g. Cannell et al., 1978, Rasmussen, 1999) and crop species (e.g. Arvidsson et al., 2014).

Also, weather conditions during the growing season can influence primary tillage methods (e.g. Wang et al., 2011): With ploughing, the grain yield was greater during the growing seasons with high precipitation compared with no-tillage, but in dry growing seasons the result was reversed. This agrees with studies with spring cereals, maize, rice (*Oryza sativa* L.), and soybean (*Glycine max* L.) (Carter, 1991; Pietola and Tanni, 2003; Wang et al., 2011; 2022). For the current study, the topsoil (0—20 cm) of no-tilled and reduced tilled clay soil was denser than for the ploughed soil because the soil dry bulk density was greater (Alakukku et al., 2007; Palojärvi et al., 2020). This agrees with studies where the topsoil bulk density was higher and saturated hydraulic conductivity lower in no-tilled and reduced-tilled soil (Rasmussen, 1999; Tebrügge and Düring, 1999; Perez-Bidegain et al., 2007; Turtola et al., 2007; Alvarez and Steinbach, 2009; Soane et al., 2012). It was evident that the effect of high precipitation in ploughed soil derives from higher temporal water storage capacity compared with other treatments (Hansen et al., 2000, Turtola et al., 2007), improving infiltration into the fine textured soil (e.g. Lipiec et al., 2006) and reducing the risk of wet soil conditions and poor soil aeration (e.g. Schjønning and Rasmussen, 2000), especially compared with no-tillage.

Relevant to this, Alakukku et al. (2012) determined the moisture content of this clay soil in the 0—30 cm layer in 2004—2011. They found that no-tilled soil stayed more moist than the soil of ploughed or reduced-tilled soil. Especially in a rainy growing season (e.g. 2004), no-tilled soil remained clearly wetter than other soils. Känkänen et al. (2011) reported that when soil stayed wet for more than two to three days during a wet growing season it hampered spring barley growth. On the other hand, during a dry growing season (e.g. 2006) soil moisture content differences among treatments was reduced when the soil dried (Alakukku et al., 2012). One reason for the greater yield on no-tilled soil under dry growing conditions might be that the roots grew rapidly into deeper layers via continuous macropores, ensuring adequate crop water uptake during dry growing season (Aura, 1999). Moreover, soil water conservation was better with reduced (Krauss et al., 2010) and no-tillage

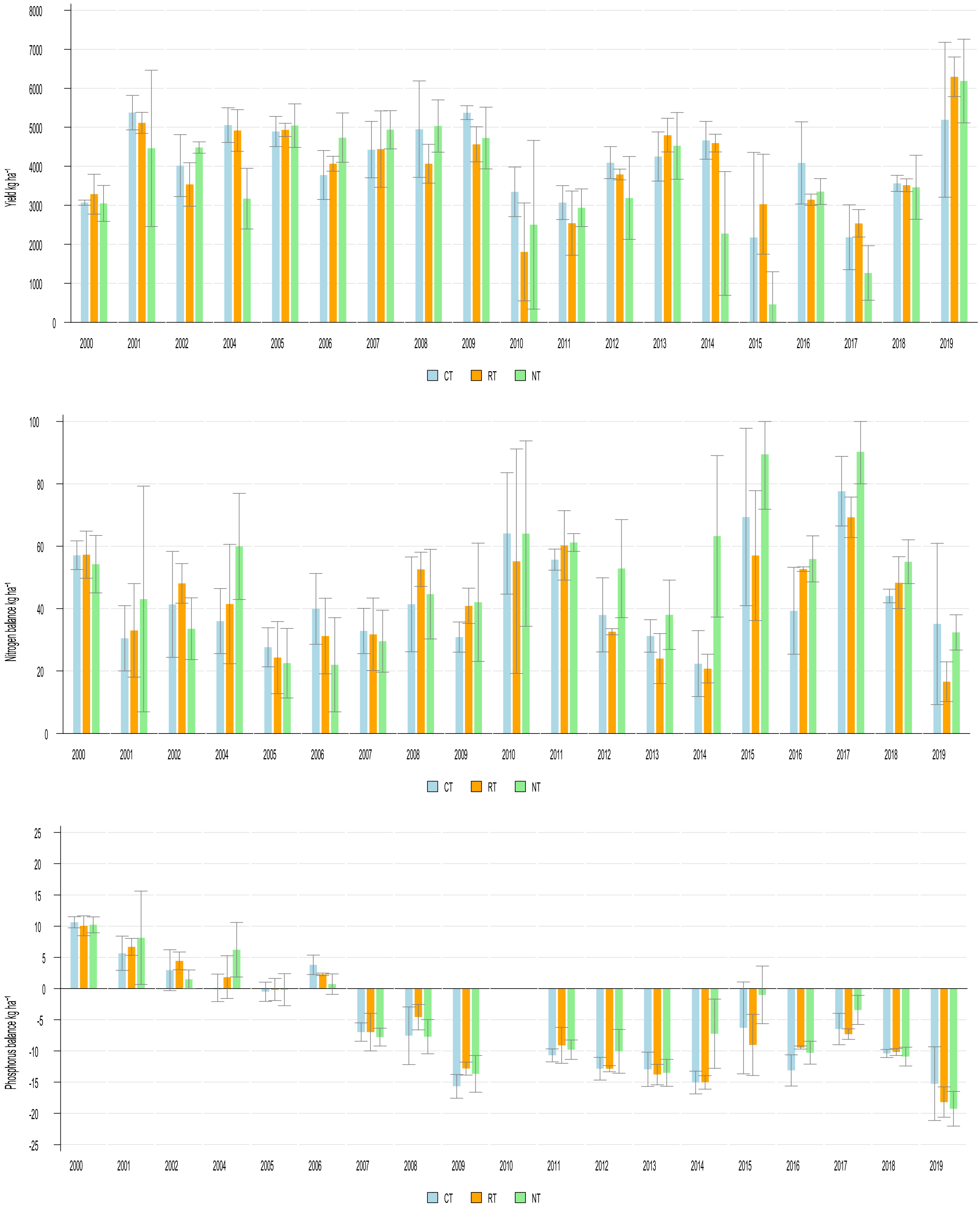

Fig. 1. Grain yield, and nitrogen balance for spring barley with 95% confidence interval lines (line at the end of the bar) in 2000–2019 and phosphorus balance for spring barley with 95% confidence interval lines (line at the end of the bar) in 2000–2009 and 2011–2019. Yield is presented at 14% moisture content. The trial was left without P fertilizer since 2008. Autumn tillage: CT=mouldboard ploughing, RT=stubble cultivation (reduced tillage), and NT=no-tillage.

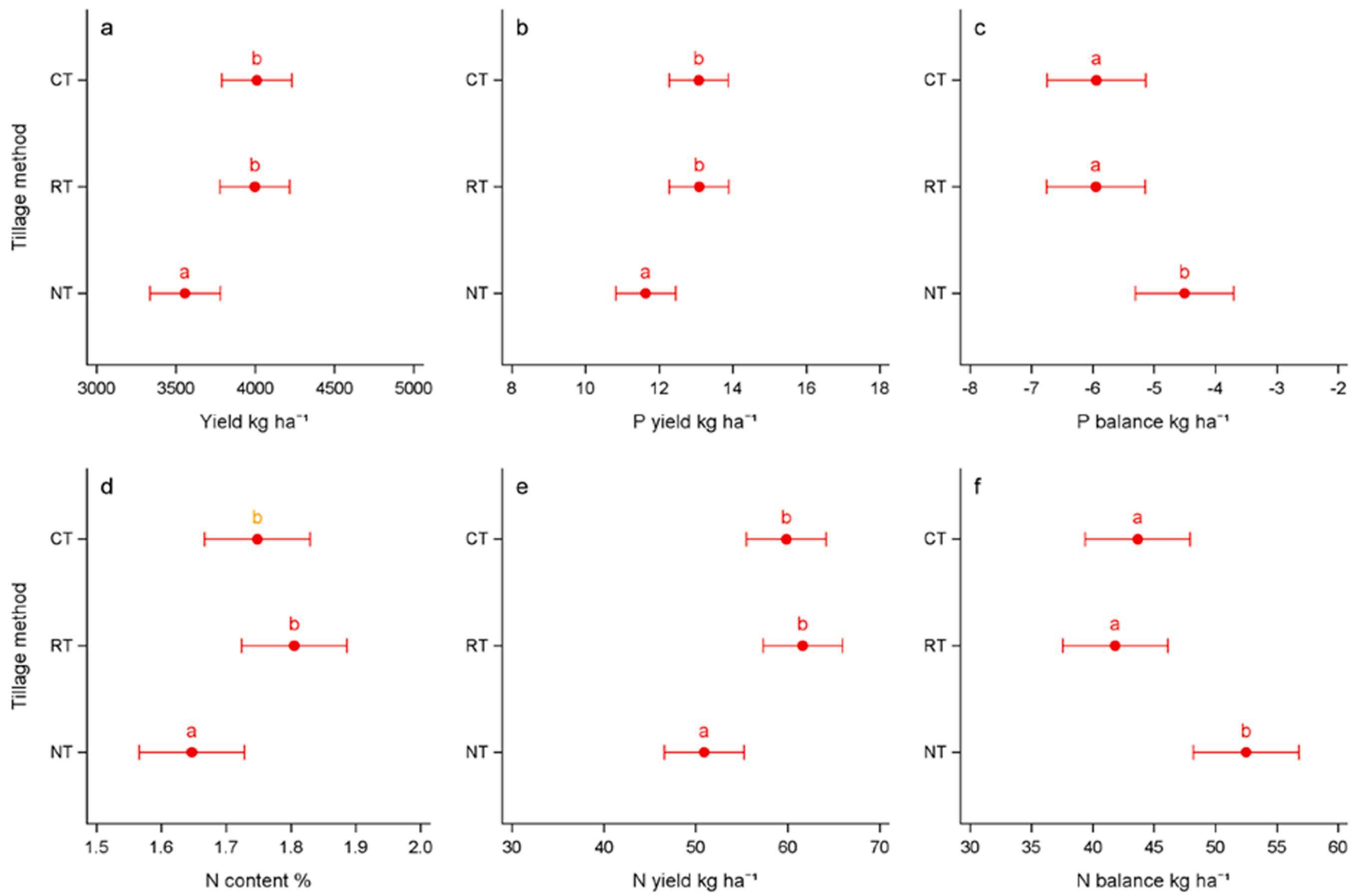

Fig. 2. Estimated means with 95% confidence intervals for grain (a), phosphorus (P) and nitrogen (N) yields (b, e), N content of grain yield (d), and P and N balances (c, f) for spring barley cultivation in 2000–2019. Comparisons with the different letters differ at p=0.05, except in Figure d, the difference between CT and NT was marginally significant (p=0.068). Autumn tillage: CT=mouldboard ploughing, RT=stubble cultivation (reduced tillage), and NT=no-tillage.

(Pietola and Tanni, 2003), respectively, than ploughing, which decreased crop sensitivity to dry conditions.

However, not only the total precipitation in a growing season but also the timing of precipitation matters. It has been found that no-tillage can slow soil drying during the sowing time compared with tilled soil (Rasmussen, 1999; Tebrügge and Düring, 1999; Pietola and Tanni, 2003; Perez-Bidegain et al., 2007; Alvarez and Steinbach, 2009; Soane et al., 2012). For instance, Känkänen et al. (2011) reported that spring barley was more vulnerable to soil wetness during early growth and soil dryness during late growth compared with spring oats and wheat during the transition to no-tillage conditions. In the current study, slow soil drying in spring delayed sowing by 3–14 days in no-tillage plots in 2004, 2007, 2015, 2017 and 2019. When having a short growing season, as in Finland (165–180 days), even a one day delay can affect crop yield negatively (Känkänen et al., 2011).

4.2. *Grain N content and nutrient yields influenced by primary tillage treatment*

There was significantly higher N content in grain yields with reduced tillage and ploughing than with no-tillage. Thus, both grain yield and grain N contents affected the N yield harvested. Pietola and Tanni (2003) observed that N content of spring cereal yields was lower in conservation tillage treatments compared with ploughing for a clay soil. However, in the research of Morrison jr and Chichnester (1994), N and P concentration in wheat tend to be high in no-tillage treatment when compared to conventional tillage. Also, Känkänen et al. (2011) did not establish N content reduction for two-rowed spring barley due to no-tillage compared with ploughing. However, soil tillage can act on nitrogen uptake in different ways. The hardness of no-tillage soil can hinder cereal root growth (e.g. Pietola, 2005, clay soil), which may reduce plant nitrogen uptake. Dense soil can also reduce the mineralization of the soil organic nitrogen, hindering crop N uptake (Ren et al., 2013).

The highest nutrient yield in this study was achieved with reduced tillage: N and P yields in seeds were 21.1% and 12.4% higher than with no-tillage, respectively. When compared with ploughing, N yield and P yield were 17.5% and 12.4% higher than no-tillage, respectively. Similarly, in Hulugalle et al. (1997), reduced tillage was associated with the highest crop nutrient uptake with cotton (*Gossypium hirsutum* L.) while Ishaq et al. (2001) study, conventional primary tillage increased wheat nutrient uptake when compared with reduced tillage. On a clay soil, Aura (1999) found that during dry growing seasons reduced tillage improved the N yield of spring cereals but during wet growing seasons the result was opposite. However, there are several studies in which primary tillage method had no significant effect on crop nutrient uptake (Malhi et al., 2006, Vogeler et al., 2009), or contrasting results where no-tillage increased crop nutrient uptake (Yadav et al., 2015, Singh et al., 2020).

4.3. *Long-term effects of primary tillage on N and P balance for spring barley cultivation*

Based on our results, both the nutrient yield and nutrient balance were related to barley yield: in general, a higher barley yield resulted a higher barley nutrient yield, which decreased the nutrient balance. Moreover, for N, the lower N content of no-tillage compared with other treatments affected the N balance by decreasing the N yield. In addition to crop yield, fertilizer use, soil type, soil pH and cultivated crop influence nutrient balance (Valkama et al., 2011, Turtola et al., 2017). Turtola et al. (2017) reported that the limit for nitrogen leaching was 20 kg/ha, which was exceeded when the nitrogen balance was 20−40 kg/ha with barley in a ploughed mineral soil. Both N and P balances have decreased in Finland during recent decades: in 2002−2017, the average N and P balance of spring barley cultivation on clay soil was 30.6 and −1.4 kg/ha, respectively (Ovaska et al., 2021). In the 1990 s, the N balance was 82−65 kg/ha and P balance 25−10 kg/ha (Luke, 2019).

On average, the lowest N balance (41.8 kg/ha) and the lowest P balance (−6.0 kg/ha) were achieved by reduced tillage over all study years. Nitrogen and phosphorus balances were 20% and 32% lower with reduced tillage when compared to no-tillage respectively. Also, with ploughing, N and P balance was 17% and 32% lower when compared with no-tillage, respectively. This agrees with the results of Turtola et al. (2017), who reported that the N balance of no-till was higher than that of reduced tilled and ploughed treatments in short-term studies on a heavy clay soil. However, N balances in the current study were higher than the average spring barley N balances in Finland (30.6 kg/ha in 2002−2017) (Ovaska et al., 2021). In the current study, P balances were lower than on average (with spring barley −1.4 kg/ha in 2002−2017, Ovaska et al., 2021), probably due to discontinuing the use of P fertilizer from 2008. Soil test P concentration for this field was at the level of most Finnish fields, when is it unlikely to produce a yield response with P fertilizer but the risk of P losses from field to environment increases (Uusitalo et al., 2007; Valkama et al., 2011). This was also true in this study, where the absence of P fertilizer since 2008 had no significant effect on barley yield.

5. Conclusion

On a heavy clay soil, grain, N, and P yields, and N content were significantly lower for no-tilled spring barley cultivation than for autumn ploughed or reduced tilled methods in this long-term study. Based on these results, it is evident that the no-tillage method was hampered by wet soil conditions more than ploughing or reduced tillage. Yield reduction increases N and P balance, indicating increased risk of nutrient losses. For this reason, securing a high crop yield is important in order to decrease the environmental impact from field to environment.

However, when choosing the tillage method for a particular field, the holistic picture should be taken account. Different soil properties, crop protection pressures, impact on the environment and the farmer's background and economic situation should all be considered when choosing the appropriate tillage method for a farm and field. Long-term field experiments are essential to evaluate the differences among primary tillage methods under variable weather conditions. In the current research, the results are based on one long-term field site. More long-term field experiments with primary tillage methods are needed to be able to determine the effect of differences in soil texture and structure on the grain, nutrient yields and nutrient balances.

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CRediT authorship contribution statement

Kauppi Katja: Data curation, Writing – original draft, Writing – review & editing. **Kaseva Janne:** Data curation, Writing – original draft, Writing – review & editing. **Jalli Marja:** Writing – original draft, Writing – review & editing. **Palojärvi Ansa:** Data curation, Methodology, Writing – original draft, Writing – review & editing. **Alakukku Laura:** Data curation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data that has been used is confidential.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127131.

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