Crop rotation and soil tillage are among key factors impacting cropping system productivity, pest management and soil health. To assess their role in northern cropping systems, we quantified the effects of crop rotation on spring wheat yield in different tillage systems based on a long-term (2005–2017) field experiment in southwestern Finland. In addition, effects of crop rotation on weeds, plant pathogens, and pest insects were assessed. Three types of crop rotation were compared: monoculture (spring wheat), 2-year rotation (spring wheat—turnip rape—spring wheat—barley) and 4-year rotation (spring wheat—turnip rape—barley—pea) under no-tillage and plowing. A diversified crop rotation improved spring wheat yield by up to 30% in no-tillage and by 13% under plowing compared with monoculture. Overall, the yield quantity and quality differences between crop rotations were higher in no-tillage plots than in plowed plots. The occurrence of weed species in spring wheat before herbicide control was highest in the four-year crop rotation and lowest in the wheat monoculture. For plant diseases, wheat leaf blotch disease severity, mainly caused by Pyrenophora tritici-repentis, was lowest in the most diverse crop rotation. On average, wheat leaf blotch disease severity was 20% less when wheat was grown every fourth year compared with wheat monoculture. The effect of crop rotation on stem and root diseases became apparent after 6 years of rotation and the disease index was lowest in the most diverse crop rotation. Neither rotation nor tillage affected the control need of wheat midge (Sitodiplosis mosellana).

Based on our results, diverse crop rotations including cereals, oilseed crops, and legumes increase yield and reduce plant disease severity of spring wheat in Finland, with the magnitude being larger in no-tillage systems.

Keywords: *Triticum aestivum*, crop sequence, biodiversity, plant protection, weeds, insects, plant diseases, no-tillage
INTRODUCTION

Northern cropping systems represent mostly Boreal zone located agroecosystems characterized by high seasonal variation leading to a short, intense growing season, and somewhat restricted selection of crops to grow. The yields are in general lower and less land area is suitable for annual crop production in the Boreal zone than other climatic regions; typically, <10% of land area is used for agriculture in north European boreal regions (Trnka et al., 2011). While the harsh winter provides some protection against major pests, climate change is predicted to increase the incidence of extreme weather events and potential pest outbreaks in northern regions (Hakala et al., 2011). Therefore, the potential for crop diversification should be considered as a strategy to prevent emerging pest problems and improve crop resilience also in the North (Altieri et al., 2015). In the future, Northern cropping systems with their already challenging production conditions are faced with increasing adaptation needs due to alterations in precipitation, temperature, and snow coverage along with the socioeconomic changes brought about by climate change (Peltonen-Sainio, 2012). This emphasizes the need to pay even more attention to the maintenance of healthy and viable soil that can sustain yielding under various biotic and abiotic crop stresses.

Planning of crop rotation and determining soil management techniques are among the most important yearly decisions that every farmer makes. Both these practices can contribute to climate change mitigation and adaptation of field cropping (Paustian et al., 2016) and impact pest management (e.g., Skellern and Cook, 2018), which links these decisions to proactive building of adaptive capacity and resilience at farm scale. To better understand the effect of crop rotation and soil management on cropping system productivity and resilience, we need long-term studies combining an analysis of the productivity component (i.e., yield quantity and quality) and the pest regulation component (incidence of pathogens, weeds, and insect pests).

In addition to the need to adapt to the changes caused by climate change in northern agriculture, modern cropping systems are currently faced with the need to develop alternatives to chemical pesticides. In 2020, the European Commission published a new biodiversity strategy that aims to halt the loss of biodiversity by 2030 (EU, 2020a), setting concrete goals for the EU food system. For example, use of pesticides and the risks they pose must be decreased by 50%. Thus, reducing the use of chemical plant protection products is one of the key objectives of EU agricultural policy. Earlier, the European Commission adopted Directive 2009/128/EC on the sustainable use of plant protection products (EU, 2009). The aim of the directive is to reduce the risks from plant protection products to human health and the environment. A key factor in achieving this goal is to promote the introduction of the IPM (Integrated Pest Management) tool. IPM aims at healthy growth and a balanced field ecosystem and encourages the use of biological methods to control pests (Vasileiadis et al., 2011).

Crop rotation is among the recommended measures to prevent pest damage in IPM production (EU, 2009). Crop rotation affects the presence of host-specific pests by disturbing their life cycle. Pest management is based on prevention, in which the crop rotation aims to create unfavorable conditions for the pest and favorable conditions for the crop. However, it is not always that vegetational diversification reduces pest incidence (Ratnadass et al., 2012) and crop diversity may also serve as a source of new pests (Keising et al., 2010).

It is broadly recognized that crop rotation often increases the crop yield (Berzsenyi and Gyoryify, 1997; Sieling et al., 2005) and provides for more sustainable crop production (Bullock, 1992; Bailey et al., 2001; Mamolos and Kalburtji, 2001). Crop rotation can also support ecological intensification, i.e., maximizing productivity per unit area while minimizing environmental impacts (Bommarco et al., 2013). Well-designed crop rotation can contribute to multiple ecosystem services through maintaining soil structure and microbial activity, improving nutrient use efficiency, and providing pest regulation services, with examples available from organic agriculture (Barbieri et al., 2017). By supporting and utilizing ecosystem services more effectively via crop diversification, agrobiodiversity (i.e., diversity at multiple levels of the agroecosystems) can be enhanced (Duru et al., 2015). Thus, overall temporal crop diversification using crop rotation represents an established, yet nonetheless increasingly important strategy to break pest and pathogen cycles, regulate nutrient dynamics, and improve yields via beneficial pre-crop effects (Sieling and Christen, 2015). Considering cropping system productivity in the long term, the aim of crop rotation is to modify the growing environment so that it meets the requirements of successful crop production of different plant species (Klein Haneveld and Stegeman, 2005).

Even though there is ample evidence on the benefits of crop rotation in general, there are knowledge gaps especially for combined effects of crop rotation on yield and on efficacy for controlling weeds, plant diseases and pest insects in spring cereal production in North European conditions. This lack of information became relevant in the early 2000’s when no-tillage cultivation became more common in Finland and there was evidence that the shift from tillage to reduced or no-tillage cultivation may cause changes in the incidence of pest species and their abundance (Paulitz, 2006). Tillage influences insect pests variably, depending on their life history strategies, i.e., growth, reproduction, survival, and dispersal (Stinner and House, 1990; Andersen, 1999). Different soil management and cultivation techniques also favor different weed species (Fonteyne et al., 2020). Non-tillage can also impact soil organic carbon sequestration as well as disease suppression and microbial biomass in soil (Palojärvi et al., 2020).

Finland belongs to the northernmost agricultural countries in Europe. In Finland, cereal-based crop rotations dominate active crop production (Peltonen-Sainio and Jauhiainen, 2019). The total area allocated to agricultural crops is currently 2.3 million hectares and in 2020, almost half of the area was sown to spring sown cereals: spring barley (Hordeum vulgare) (458,000 ha), oats (Avena sativa) (348,000 ha), and spring wheat (Triticum aestivum) (210,000 ha) (Luke, 2020a). Forage grasses are cultivated on the other half of the area, while oil and protein crops cover a minor part of the cultivated area. In the past 20
years, spring wheat cultivation area in Finland has increased ca. 70% while the area allocated to oilseed crops has decreased by 43% (Supplementary Figure 1).

The change from dairy farming and intensive grass production to cereal-dominated crop production has affected the occurrence of pest species (weeds, plant diseases, and insect pests) in Finnish fields. The most common weed species in spring cereal fields are Viola arvensis (field pansy), Stellaria media (chickweed), Galeopsis ssp. (hemps-nettle), Galium spurium (false cleavers), and Lamium purpureum (red dead-nettle) (Salonen et al., 2011). For plant diseases in spring wheat, the most common are seed- and straw-borne leaf spot diseases, stagonospora blotch (Parastagonospora nodorum) and tan spot (Pyrenophora triticirepentis), the incidence of which has increased during recent years together with the increased area of reduced tillage, especially in wheat monoculture (Jalli et al., 2011, 2020). The main insect pests that damage spring wheat in Finland are orange wheat blossom midge (Sitodiplosis mosellana), the bird cherry-oat aphid (Rhopalosiphum padi), and occasionally the frit fly (Oscinella frit). The frequency and amplitude of pest outbreaks vary considerably in time and space, and the growing conditions play an important role in their occurrence (Kurppa, 1990).

Based on a long-term data, if no plant protection practices are used, weeds cause on average a 200 kg/ha yield reduction in spring cereal production. In addition to reduced crop yield, pests also decrease crop nutrient use efficiency significantly (Kauppi et al., 2021), which hampers the crop’s ability to grow (Di and Cameron, 2002; Meisinger and Delgado, 2002).

The reasoning underlying establishment of the long-term trial presented in this study was the practical concern in Finnish cereal production in the early 2000’s: how the growth of spring wheat, a crop having common pests, leaf blotch diseases and wheat midge, overwintering in soil or plant debris, and with cultivation being widely based on cereal monoculture, will be affected by the changes in tillage systems. There was also interest in revealing whether more diverse cropping system could help to reduce the possible risks of moving to no-tillage. Thus, the main objective of this study was to find out how different crop rotations affect spring wheat yield and the incidence of weeds, plant pathogens and insect pests common in Finnish spring wheat production in different tillage systems. Conclusions are based on the results gathered over the 13 years of the field study.

MATERIALS AND METHODS

Location and Growing Conditions
A long-term field trial was conducted at research station fields of Luke, Natural Resources Institute Finland, in Jokioinen (60° 49’N, 23° 28’E) in southwest Finland in 2005–2017. Finland, one of the northernmost high latitude European countries, represents Boreal climate zone and typical northern growing conditions (Metzger et al., 2005). Soil type in the trial area was sandy clay with pH 6.1–6.5 and 7.2 mg/l phosphorous in soil. Before 2005, the main crops in the field were forage grass, spring wheat, spring barley and oats and before 2003, the field was plowed annually. Annual weather conditions during growing seasons varied considerably in 2005–2017 in Jokioinen (Supplementary Table 1). The long-term (1981–2010) effective temperature sum in May–September in Jokioinen is 1,269° and cumulative precipitation 316 mm. The coolest season was in 2017, with an effective temperature sum of 1,136 and the warmest in 2006, with an effective temperature sum of 1,540. Also, year 2006 was the driest season, with cumulative precipitation of 207 mm while in 2011, the cumulative precipitation was highest, with 414 mm of rain.

Trial Design
In the field experiment, three types of crop rotation were compared: CR1 spring wheat monoculture, CR2 2-year rotation (spring wheat—spring turnip rape (Brassica rapa subsp. oleifera)—spring wheat—spring barley) and CR4 4-year rotation [spring wheat—spring turnip rape—spring barley—field pea (Pisum sativum)] (Table 1). All crop rotation treatments were sown both in no-tillage and plowed soil and formed 16 treatments in total. Each treatment had four replicates.

The plot size was 6 × 15 m. Sowing time ranged between May 5th to July 30th and harvest between August 12th and September 28th (Supplementary Table 1). Tillage plots were plowed in autumn (October, except in 2008 November) and tilled to 5 cm depth with a combined power harrow before sowing. The plowed plots were sown with combined drill seeding machines with 12.5 cm crop rows. Fertilizers were placed between every second crop rows (25 cm apart). No-tillage plots were directly sown to 3–5 cm depth with a combined drill-seeding machine with double disk coulters that placed seed and fertilizer in the same 15 cm crop row. Seeds were sown at 650 seeds/m2 for spring wheat, 500 seeds/m2 for spring barley, 9.6 kg seeds/ha for spring turnip rape and 110 seeds/m2 for field pea. The fertilizer levels followed the EU-agricultural support council directive (EU, 2020b): 120 nitrogen (N) kg/ha for spring wheat, 90 N kg/ha for spring barley, 120 N kg/ha for spring turnip rape, and 50 N kg/ha for field pea (Supplementary Table 2). After pea, the amount of N-fertilizer was reduced by 10 kg/ha.

Plant Protection Treatments
In cereals, weeds were controlled annually with herbicides at tillering stage BBCH 20–24 (Bleiholder et al., 1997). The product was chosen according to the weed species. In addition, no-tillage plots were treated with glyphosate in spring before sowing, except in 2014–2016, when both the no-tillage and plowed plots were treated with glyphosate after the harvest. Glyphosate concentration ranged from 3 to 71/ha based on the weed pressure.

For spring wheat and spring barley, fungicide-dressed seed was used to control seed-borne diseases. No foliar fungicide treatments were applied for any of the crops. Turnip rape seed was coated with neonicotinoids to control flea beetles (Phyllotreta sp.). Insecticides were used when control thresholds were exceeded in different crops. Flea beetles and pollen beetles (Meligethes aeneus) were controlled in turnip rape annually with sprayed insecticides (pyrethroids and neonicotinoid), while pea moths (Cydia nigricana) were controlled with pyrethroids in peas only in the years 2009–2011.
In cereals, bird cherry-oat aphid was sprayed with pyrethroids in 2005.

### Field Observations

Before herbicide treatments (BBCH 20–24) the number of weeds was counted by species from five 0.1 m² subsample areas in each plot. For data analyses, weed species were divided into five groups: Group1, common spring germinating weeds in cereals (Viola arvense, Chenopodium album); Group2, other spring germinating weeds (Galeopsis, Galium spurium, Lamium purpureum); Group3 weeds germinating both in spring and autumn (Stellaria media, Fumaria officinalis, Taraxacum officinale); Group4 grasses and biennial plants (Agropyron repens, Poa annua, Sonchus arvensis, Cirsium arvense), and Group5, the remaining species.

The occurrence of plant diseases was evaluated twice per growing season. For stem and root disease assessments, a random sample of 30 plants was collected from each spring wheat plot at milk ripening stage (BBCH 75–77). Stems and roots of the plants were rinsed with water and the symptoms were assessed. The plants were divided into five groups (A–E) according to the severity of the symptoms and a disease index was assessed. The plants were divided into five groups (A–E) according to the severity of the symptoms and a disease index was calculated from the number of the plants in different groups. The disease index \( A = D_{\text{index}} \) was calculated from the number of the plants in different groups.

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(m = 2005,...,2017), rep*year_{im} is random effect of year-
by-replication interaction, rep*block(rep)_{ijm} is random effect of 
incomplete block-by-year interaction, rotation*year_{km} is 
rotation-by-year interaction, tillage*year_{im} is tillage-by-year 
interaction, rotation*tillage*year_{klm} is rotation-by-tillage-by-
year interaction and finally r_{ijklm} is residual error. Seed yield 
consists of two main components: number of seeds per hectare, 
and single seed weight. Only seed yield and single seed weight 
(1,000 seed weight) were measured. The number of seeds per 
hectare was calculated as a ratio of two measured variables. The 
result was presented as number of seeds per m².

The model was fitted using SAS/MIXED with the REML-
estimation method. This model assumes that the data follow 
the normal probability distribution, and the variances of the 
populations are equal. These assumptions were checked using 
scatter plots of residuals and predicted values. Some variables 
were not normally distributed, also error variance varied among 
years. Transformations were used to ensure assumptions: loge 
for total number of weeds, for number of weeds in Groups 2– 
5, and for total number of monocotyledonous weeds (grass-type 
weeds) and square-root transformation for damaged kernels and 
for number of weeds in Group 1.

After modeling, the results were presented so that eight 
rotations were categorized as three different types of rotation: 
spring wheat monoculture CR1, two-year rotation CR2 and four-
year rotation CR4. Data were gathered from several years and 
cultivated crops varied from rotation to rotation in most of 
years. Only years having spring wheat in all three different types 
of rotation (CR1, CR2, CR4) were included to the statistical 
modeling: 2007, 2008, 2010, 2011, 2012, 2014, 2015, and 2016. In 
addition, years were combined into three periods: Period1 (2007, 
2008), Period2 (2010, 2011, 2012) and Period3 (2014, 2015, 2016). 
Statistical tests and estimates were calculated for three periods 
and three rotations using estimate and contrast commands in 
SAS/MIXED. However, original statistical tests of treatments 
(rotation, tillage and their interaction) and year-by-treatments 
interaction were presented also (F-tests). The statistical model 
was fitted using version 9.4 of SAS/MIXED.

RESULTS

Spring Wheat Yield

The spring wheat plot yield in 2007–2017 ranged between 1,314 
(no-tillage CR1 in 2015) and 5,842 (plowed CR4 in 2015) kg/ha 
(Figure 1). The average spring wheat yield over all treatments and 
years was 4,046 kg/ha. In the most diverse crop rotation (CR4), 
the average spring wheat yield was on average 21% higher than 
the yield in the wheat monoculture CR1 (p < 0.001). In CR2, 
where wheat was cultivated every second year, the average yield 
was 15% higher than in the wheat monoculture (p < 0.001).

Differences in the spring wheat yield among three different 
crop rotations were apparent already during Period 1 and 
increased further in Period 2 and Period 3 (Table 2). The yield 
differences among the tested crop rotations were higher in the 
no-tillage than in the plowed treatments. In both tillage systems, 
the yield was lowest in wheat monoculture for all time periods 
except during Period 1 when no-tillage CR4 plots had the lowest 
yield. When plowed, the yield of CR4 plots was, on average, 
13% higher than in the monoculture plots, whereas a 30% yield 
difference was reached in the no-tillage plots. The wheat yields in 
monoculture (CR1) were, on average, 14% lower in the no-tillage 
plots than in plowed plots. In crop rotations CR2 and CR4, there

TABLE 2 | The average spring wheat yield (kg/ha) in different tillage systems, time periods, and crop rotations.

| Both tillage systems | Plowed | No-tillage |
|----------------------|--------|------------|
| CR1 | CR2 | CR4 | s.e. | P-value | CR1 | CR2 | CR4 | s.e. | P-value | CR1 | CR2 | CR4 | s.e. | P-value |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Period1 | 4232 | 4548 | 4317 | 111 | 0.03 | 4120 | 4351 | 4496 | 141 | 0.19 | 4343 | 4745 | 4136 | 141 | <0.01 |
| Period2 | 3226 | 3661 | 4159 | 101 | <0.001 | 3315 | 3664 | 3965 | 126 | <0.01 | 3137 | 3651 | 4354 | 126 | <0.001 |
| Period3 | 3594 | 4355 | 4646 | 111 | <0.001 | 4201 | 4619 | 4652 | 126 | 0.03 | 2986 | 4090 | 4640 | 126 | <0.001 |
| Mean | 3615 | 4142 | 4381 | 87 | <0.001 | 3849 | 4194 | 4356 | 107 | 0.01 | 3382 | 4089 | 4406 | 107 | <0.001 |

CR1, wheat monoculture; CR2, wheat every 2nd year; CR4, wheat every 4th year. 
Period1 (years 2007 and 2008), Period2 (years 2010, 2011, and 2012), and Period3 (years 2014, 2015, and 2016).
was no significant difference in the average wheat yield between the no-tillage and plowed plots.

Crop rotation affected positively the produced seeds (1,000 seeds/m²), hectoliter weight and thousand seed weight (Figure 2). The effects were more significant in no-tillage plots, except for thousand seed weight, which was positively affected by crop rotation also in plowed plots (Table 3). The effect of crop rotation on the number of seeds per square meter increased over time. During the last period (Period 3), the number of seeds per square meter was 50% higher in CR4 than in CR1. When plowed, the corresponding difference was 7%.

The spring wheat grain nutrient uptake (kg/ha) in grain yield was estimated based on the spring wheat yield results. Over the two tillage systems the nitrogen uptake in different crop rotations and time periods was 60–86 kg/ha and phosphorous uptake 10–15 kg/ha (Table 4). Crop rotation had a statistically significant effect on nutrient uptake in Periods 2 and 3. The average nitrogen uptake in plowed plots in CR4 was 14% higher and the average phosphorous uptake 17% higher than in the CR1 plots. In no-tillage plots, the corresponding figures were 30 and 27%, respectively.

**Occurrence of Weeds**

In 2007, at the time of the first observations, the weed density in spring wheat plots was quite even in all the crop rotations, 80–115 plants/m². The main weed species in the trial were G. spurium, L. purpureum, S. media, F. officinalis, and Trileurospernum inodorum. Among years, there were significant differences in the number of weeds germinated (Figure 3). In spring wheat monoculture (CR1), the weed density ranged between 58 and 200, in CR2 between 117 and 357, and in CR4 between 96 and 416 plants/m².

In different crop rotations, the weed density was affected by the tillage type ($p < 0.001$). The effect of crop rotation on weed density was visible already at Period 1 and the differences were more significant in no-tillage than in plowed environments (Table 5). The average number of weeds in plowed plots was 154 and in no-tillage plots 201 plants/m².

The effect of crop rotation and tillage system varied among different weed species groups (Table 6). Except in Group 4 (A. repens, P. annua, S. arvensis, and C. arvense) the weed density was lowest in CR1 and highest in CR4. The density of Group 3 weeds (S. media, F. officinalis, and T. officinale) was higher in plowed plots and the density of Group 4 and Group 5 (other weeds) in no-tillage plots.

**Plant Disease Severity**

The stem and root disease severity in spring wheat was at a low level and decreased over time (Figure 4). The disease index in different treatments ranged between 2.9 (plowed CR4 in 2015) and 39.6 (no-tillage CR1 in 2008) during the trial period when the maximum potential value was 100. The average stem and root disease indexes were highest in the CR1 plots and lowest in CR4 plots, both in no-tillage and plowed environments, except during Period 1 when the differences were not statistically significant. The average disease severity was slightly higher in no-tillage (21.4) than in plowed (19.6) plots ($p < 0.001$) (Table 7). The main causal agents of the stem and root infections were Fusarium culmorum and F. avenaceum. The incidence of other Fusarium species was minor. No take-all (Gaeumannomyces graminis) was identified on stems.

The dominant leaf spot disease on spring wheat was tan spot, which was visible in no-tillage CR1 plots soon after emergence.
Also, some stagonospora blotch was detected at BBCH 75. The observations on leaf spot diseases were combined into a single value—leaf blotch disease. Low levels of powdery mildew (Blumeria graminis) were observed occasionally and it was distributed evenly across the trial plots (no data shown).

The average leaf blotch disease severity at BBCH 75 was quite even during the trial period, except in 2008, when it was lower and in 2011, when it was higher than average (Figure 5), and no major differences in disease severity were observed between the two tillage systems. The average leaf blotch severity was highest in CR1 and lowest in CR4 in all time periods and both tillage systems (Table 8). On average, leaf blotch disease severity was 15% lower in CR2 than CR1 and 20% lower in CR4 than CR1.

The incidence of Fusarium species in spring wheat yield was analyzed in 2011–2017. The incidence varied from 42% in 2015 to 100% in 2012. The main fungal species detected were F. avenaceum (23% seeds infected), F. poae (17% seeds infected), and F. graminearum (14% seeds infected). The incidence of F. avenaceum was highest in CR4 and lowest in CR1 (p < 0.01). In contrast, the incidence of F. poae was highest in CR1 and lowest in CR4 (p < 0.01). Crop rotation had no effect (p = 0.40) on total Fusarium incidence on wheat seeds.

### Insect Pests’ Prevalence

Occurrence of wheat midges varied widely among years, but no chemical control of midges was needed. Crop rotation and tillage had no effect on the amount of kernels damaged by wheat midge (p = 0.76 and p = 0.42, respectively), but some differences were found in individual years. In 2015, the amount of kernels damaged by wheat midge was highest in spring wheat monoculture (CR1) and lowest in the most diverse crop rotation (CR4) (Table 9).

The abundance of other insect pests, including flea beetles, frit fly, and aphids, varied among growing seasons. Their numbers in yellow sticky traps were higher in plowed plots in several years but the difference among rotations was not monitored (Table 10).
Aphids achieved the threshold for insecticide treatment in 2005. Abundance of flea beetles was especially high in 2007. Frit fly risk was high when sowing date was late. However, minor damage was attributable to these insect pests.

**DISCUSSION**

Our long-term study made it possible to estimate the short- and long-term effects of different crop rotations on spring wheat growth and pest occurrence under northern European conditions. Crop rotations, as well as pre-crop values, are difficult to model and considerable replication is needed. The effects observed also vary greatly depending e.g., on the growing conditions. For example, variation in weather events impacts crop growth and soil processes that contribute to the yield results (Sieling and Christen, 2015). Both short- and long-term effects can be mutually confounded, and long-term studies are needed to separate effects.

In our study, the same rotations were repeated several times, which allowed the identification of the true impact of rotations: most differences were based on pre-crop values of different crops in the first cycle (short term effect). In the later cycles, increased differences between rotations were the true long-term effects of rotations. In addition, we used eight different rotations, but rotations were compressed into three different types in the statistical analysis. This compression increased the number of replications and allowed one to see beyond the data and make wider statistical inference.

**Effect of Crop Rotation on Spring Wheat Yield**

The systemic effects of crop rotation were visible since 2010, after 5 years of the rotation experiment. A diversified crop rotation improved spring wheat yield most, when combined with no-tillage. Under plowing, the yield increase by rotation was also significant, but lower compared with no-tillage. The phenomenon was similar both in low and high yield level years. According to Berzsenyi and Gyorffy (1997) the yield-increasing effect of crop rotation is negatively correlated with the ratio of Table 5 and Table 6.
wheat in the sequence, which was the case in our study also. The yield differences between CR4, CR2, and CR1 were consistently higher in no-tillage plots than plowed plots mainly due to lower yield levels in CR1 in no-tillage plots. The results are in line with other crop rotation trials incorporating wheat (Berzensy et al., 2000; López-Bellido et al., 2001; Soon and Clayton, 2002; Sieling et al., 2005; Smith et al., 2008; Wozniak, 2020) even though most of the previous research was carried out with winter wheat rather than spring wheat.

The largest benefits in terms of yield were found using the most diverse crop rotation, having spring wheat every fourth year. In general, inclusion of crops from various families (cereals, oilseeds, and legumes) in rotations and lengthening the rotation cycle adds agroecological complexity through increased variation in shoot and root characteristics, biological and chemical traits, and crop management. In the current study, legumes were included only in CR4, where pea was a pre-crop for wheat. Pea has as good pre-crop value (Babublicová, 2016) and may increase wheat yield by 40% compared with wheat monoculture (Stevenson and van Kessel, 1996). In our study, the pre-crop value was not analyzed as such. However, the fertilizing effect of pea was considered by decreasing the nitrogen fertilizer level by 30 kg/ha when spring wheat was grown after pea. The differences in yield levels in different crop rotations might have been even larger if the nitrogen levels were same despite the pre-crop. According to Stevenson and van Kessel (1996), 92% of the yield advantage in the pea–wheat rotation is attributed to non-N rotation benefit.

Seed number is, in most cases, the major yield component that determines yield (Peltonen-Sainio et al., 2007). According to Galantini et al. (2000) crop rotation has a positive effect on spike number, but not number on spikelets per spike. In our study, the number of seeds per unit area was significantly higher in CR4 than in CR1. This may have resulted from positive changes in soil texture and microbial biomass (Bullock, 1992; Chan and Heenan, 1996; Govaerts et al., 2007) as well as decreased disease pressure via crop rotation (Bockus, 1992; Paulitz et al., 2010).

The average spring wheat yield in the trial was 4,050 kg/ha, which was close to the average spring wheat yield on Finnish farmers’ fields in 2019, 4,300 kg/ha (Luke, 2020c). However, weather conditions, especially precipitation, greatly influenced the yield: the lowest yield, on average, was achieved in 2010 when the precipitation was below and the effective temperature sum above the long-term average. The highest yield was achieved in 2015, when weather conditions were very close to the long-term average. Weather conditions relating to different plant growth stages in particular affect the yield formation: for example, drought at the flowering stage decreases the number of fertile florets (Rajala et al., 2009).

Effect of Crop Rotation on Weeds

Weeds grow best in the presence of crops with the same growth requirements (Liebman and Dyck, 1993). In our trial, the weed population was greatest in a diverse crop rotation, with residual effects from previous weed management that may persist for up to 2 years depending on the rotation (Légère and Stevenson, 2002). The main reason for the increased weed density in the more diverse crop rotation was the lack of effective weed control methods in turnip in the no-tillage system. During the implementation of the experiment, wheat monoculture had effective herbicide treatment every year while in CR2 and CR4 there was no herbicide available for turnip rape in the no-tillage system. The weed control in field peas with the active ingredients available (bensulfide and acloflan) was not as effective as weed control in wheat. Crop rotation may decrease the density of perennial weeds compared with monoculture (Chamanabadi et al., 2009), but in our trial the efficacy could not be measured because of the glyphosate treatments in spring before sowing or in autumn after the harvest.

The most common weeds in the current trial, G. spurius, L. purpureum, S. media, F. officinalis, and T. inodorum, represent the typical weeds growing on Finnish cereal fields (Salonen et al., 2011). In monoculture plots, the mean weed density before herbicide treatment was 114 weeds/m² and it was double in CR4 plots while the average weed density in Finnish spring cereal fields is 160 weeds/m² (Salonen et al., 2011). The phenomenon of higher weed density in CR2 and CR4 compared with CR1 was visible already at Period1, and especially in no-tillage plots. Liebman and Dyck (1993) reported contrasting findings in their literature survey where in 21 cases out of 27 there were fewer weeds in crop rotations than in monoculture. In several studies, crop rotation is reported to be an effective tool to control weeds (Mertens et al., 2002; Zawislak and Kostrzewska, 2005; Fonteyne et al., 2020). However, Bárberi and Cascio (2001) reported that crop rotation only slightly decreased major weed species abundance when tillage had a large negative influence on weed seedbank size, as was the case in our study where plowing was a more effective tool to control weeds than crop rotation.

Effect of Crop Rotation on Plant Diseases

According to Kennedy and Huseth (2020), pest and pathogen infestations are associated with phylogenetic distance of crop
plants and related native plants. In our trial, wheat leaf blotch disease damage was greatest in spring wheat monoculture and the differences were more significant in no-tillage than in plowed plots. The most common leaf spot disease in the trial was tan spot, which was detected on the upper leaves of the crop. The most significant source of tan spot infection is plant debris from the previous growing season, in which case the crop rotation plays the greatest role in its control (Krupinsky et al., 2002). Moreover, no-tillage is a major factor increasing the severity of tan spot compared with plowing (Jørgensen and Olsen, 2007). This observation is supported by Jørgensen et al. (2020), who demonstrated the effect of tillage system and crop rotation on soil microbial communities and the general disease suppression. There is no known cultivar resistance to stem and root diseases in Nordic spring wheat cultivars and the possibilities for chemical control are limited. Therefore, the importance of crop rotation and tillage methods, and their interaction, is emphasized. Effective weed control and straw waste treatments also reduce the risk (Paulitz, 2006).

Effect of Crop Rotation on Wheat Midges

Wheat midges are important pests of spring wheat: infestations of 30, 60, and 90% reduce the yield of spring wheat by 40–65 and 79%, respectively (Olfert et al., 1985). Considered as a whole, crop rotation and tillage had no effect on wheat midge damage in the current study. However, the amount of seeds damaged by wheat midge differed (CR1>CR4) in an individual year. In Finland, risk of orange wheat blossom midge is concentrated in the main cropping areas of wheat, where barley and oats are also commonly cropped. Because pupae of wheat midges survive in soil for several years, high frequency of wheat cropping in combination with no-tillage can increase the risk of damage. For example, Elliot et al. (2002) reported that a population of wheat midge was 2.2 times higher in no-tillage conditions than in tilled systems. However, the coincidence of midge flight peak and ear emergence of wheat and favorable egg-laying conditions, are important factors, and the risk varies widely annually.

Overall, only if insect species are host-specific and their dispersal ability is low, is crop rotation a powerful tool to control them (Coaker, 1987). However, reliable estimation of the effect of crop rotation on mobile insect pests at the scale of experimental plots is difficult to verify and larger plots are needed. Furthermore, in the case of insect pests, an area-wide pest management system and crop rotation on a regional scale is often needed (Chandler and Faust, 1998; Sexon and Wyman, 2005; Huusela-Veistola and Jauhiainen, 2006).

### TABLE 7 | The average stem and root disease index (0–100) in spring wheat in different tillage systems, time periods, and crop rotations.

| Both tillage systems | Plowed | No-tillage |
|----------------------|-------|-----------|
|                      | CR1   | CR2       | CR4   | s.e. | P-value | CR1   | CR2       | CR4   | s.e. | P-value |
| Period1              | 31.1  | 29.5      | 29.5  | 0.89 | 0.26    | 30.3  | 28.9      | 28.7  | 1.16 | 0.58    |
|                      |       |           |       |      |         | 31.9  | 30.0      | 30.2  | 1.16 | 0.41    |
| Period2              | 21.0  | 19.2      | 17.0  | 0.74 | <0.001  | 19.2  | 18.1      | 15.5  | 0.96 | 0.02    |
|                      |       |           |       |      |         | 22.7  | 20.2      | 18.5  | 0.96 | 0.01    |
| Period3              | 17.3  | 15.8      | 13.9  | 0.74 | <0.01   | 16.5  | 15.2      | 13.8  | 0.96 | 0.15    |
|                      |       |           |       |      |         | 18.2  | 16.4      | 14.0  | 0.96 | 0.01    |
| Mean                 | 22.1  | 20.5      | 18.9  | 0.51 | <0.001  | 21.0  | 19.7      | 18.2  | 0.63 | 0.01    |
|                      |       |           |       |      |         | 23.3  | 21.2      | 19.7  | 0.63 | <0.001  |

CR1, wheat monoculture; CR2, wheat every 2nd year; CR4, wheat every 4th year. Period1 (years 2007 and 2008), Period2 (years 2010, 2011, and 2012), and Period3 (years 2014, 2015, and 2016).
Crop Rotation Strategy

Considering crop rotation as a strategy to support several agroecosystem functions or services (e.g., Duru et al., 2015; Wozniak, 2019), our results suggest that higher yields were mostly accompanied by beneficial belowground interactions such as improved nutrient dynamics and soil functions over the rotational cycles. A recent meta-analysis on impacts of agricultural diversification on yield and other ecosystem services concluded that crop diversification had mostly a positive impact on soil fertility, nutrient cycling and pest control (Tamburini et al., 2020). However, for yield in particular, high context specificity was established. In the same analysis, reduced tillage had a predominantly positive impact on soil fertility and nutrient cycling, a neutral or negative impact on yield and climate and water regulation, and a negative impact on pest control (Tamburini et al., 2020).

The positive effect of crop rotation on crop nutrient uptake (Venkatesh et al., 2017) was also verified in our study: spring wheat had better N and P uptake in CR2 and CR4 than in CR1 with both tillage conditions, the effect being even higher in no-tillage conditions as also reported by Malhi and Lemke (2007). Higher nutrient balance increases the risk of nutrient leaching.

### TABLE 8 | The average leaf blotch disease severity (%) in spring wheat in different tillage systems, time periods, and crop rotations.

| Period  | CR1  | CR2  | CR4  | s.e. | P-value | CR1  | CR2  | CR4  | s.e. | P-value | CR1  | CR2  | CR4  | s.e. | P-value |
|---------|------|------|------|------|--------|------|------|------|------|--------|------|------|------|------|--------|
| Period1 | 17.1 | 13.7 | 12.3 | 1.05 | <0.01  | 15.3 | 13.3 | 12.6 | 1.4  | 0.41   | 19.0 | 14.1 | 12.0 | 1.4  | <0.01  |
| Period2 | 52.8 | 45.5 | 42.9 | 1.05 | <0.001 | 54.4 | 47.8 | 47.6 | 1.4  | <0.01  | 51.3 | 43.1 | 38.2 | 1.4  | <0.001 |
| Period3 | 22.3 | 19.4 | 18.5 | 0.91 | 0.02   | 20.8 | 19.6 | 18.3 | 1.2  | 0.37   | 23.7 | 19.3 | 18.8 | 1.2  | 0.01   |
| Mean    | 29.5 | 25.2 | 23.7 | 0.73 | <0.001 | 28.8 | 25.8 | 25.0 | 0.9  | 0.01   | 30.2 | 24.6 | 22.4 | 0.9  | <0.001 |

CR1, wheat monoculture; CR2, wheat every 2nd year; CR4, wheat every 4th year. Period1 (years 2007 and 2008), Period2 (years 2010, 2011, and 2012), and Period3 (years 2014, 2015, and 2016).

### TABLE 9 | The average amount of kernels damaged by wheat midge in spring wheat in different tillage systems, time periods, and crop rotations.

| Period  | CR1  | CR2  | CR4  | s.e. | P-value | CR1  | CR2  | CR4  | s.e. | P-value | CR1  | CR2  | CR4  | s.e. | P-value |
|---------|------|------|------|------|--------|------|------|------|------|--------|------|------|------|------|--------|
| Period1 | 5.6  | 5.2  | 5.0  | NA   | 0.6    | 5.7  | 5.9  | 4.5  | NA   | 0.1    | 5.4  | 4.5  | 5.5  | NA   | 0.2    |
| Period2 | 2.2  | 2.6  | 2.7  | NA   | 0.3    | 2.3  | 2.7  | 2.4  | NA   | 0.6    | 2.2  | 2.6  | 3.0  | NA   | 0.2    |
| Period3 | 3.0  | 2.7  | 2.3  | NA   | 0.2    | 3.6  | 2.8  | 2.9  | NA   | 0.3    | 2.4  | 2.5  | 1.7  | NA   | 0.2    |
| Mean    | 3.3  | 3.3  | 3.1  | NA   | 0.8    | 3.5  | 3.5  | 3.1  | NA   | 0.4    | 3.0  | 3.1  | 3.2  | NA   | 0.9    |

CR1, wheat monoculture; CR2, wheat every 2nd year; CR4, wheat every 4th year. Period1 (years 2007 and 2008), Period2 (years 2010, 2011, and 2012), and Period3 (years 2014, 2015, and 2016).

### TABLE 10 | Abundance of pest insects in spring wheat monitored with yellow sticky traps in 2005–2017.

| Year   | Bird cherry-oat aphid | Frit fly | Flea beetles | Bird cherry-oat aphid | Frit fly | Flea beetles | Bird cherry-oat aphid | Frit fly | Flea beetles |
|--------|-----------------------|---------|--------------|-----------------------|---------|--------------|-----------------------|---------|--------------|
| 2005   | 1.0                   | 3.4     | 1.0          | 1.3                   | 5.1     | 1.2          | 0.8                   | 1.6     | 0.9          |
| 2006   | 0.7                   | 5.2     | 3.7          | 0.7                   | 6.0     | 4.6          | 0.7                   | 4.5     | 2.9          |
| 2007   | 1.1                   | 11.8    | 13.2         | 1.4                   | 17.3    | 22.2         | 0.9                   | 6.3     | 4.1          |
| 2008   | 0.6                   | 6.0     | 5.1          | 0.4                   | 6.4     | 6.0          | 0.8                   | 5.5     | 4.1          |
| 2009   | 0.2                   | 2.0     | 11.7         | 0.3                   | 3.4     | 20.5         | 0.2                   | 0.6     | 2.8          |
| 2010   | 0.8                   | 6.6     | 3.9          | 0.9                   | 10.3    | 3.1          | 0.6                   | 2.8     | 4.8          |
| 2011   | 0.9                   | 1.1     | 16.1         | 0.9                   | 1.3     | 21.0         | 0.8                   | 0.9     | 11.2         |
| 2012   | 1.5                   | 1.2     | 3.1          | 1.2                   | 1.6     | 3.3          | 1.8                   | 0.9     | 3.0          |
| 2013   | 0.1                   | 3.3     | 1.2          | 0.1                   | 5.5     | 1.8          | 0.1                   | 1.1     | 0.6          |
| 2014   | 3.0                   | 13.5    | 1.3          | 3.2                   | 19.0    | 1.9          | 2.8                   | 7.9     | 0.7          |
| 2015   | 0.2                   | 8.7     | 1.0          | 0.2                   | 10.7    | 1.3          | 0.3                   | 6.8     | 0.7          |
| 2016   | 4.1                   | 1.1     | 0.0          | 4.7                   | 1.4     | 0.1          | 3.6                   | 0.9     | 0.0          |
| 2017   | 0.0                   | 0.4     | 0.4          | 0.0                   | 0.5     | 0.4          | 0.0                   | 0.4     | 0.4          |

CR1, wheat monoculture; CR2, wheat every 2nd year; CR4, wheat every 4th year. Period1 (years 2007 and 2008), Period2 (years 2010, 2011, and 2012), and Period3 (years 2014, 2015, and 2016).
Crop rotation planning for northern agriculture involves considering multiple objectives, including suitability for a particular farm and locality, and the economic benefits (Peltonen-Sainio et al., 2019). Both crop diversification and reduced soil tillage represent potential efforts toward more agrobiodiverse and climate-resilient agriculture (Altieri et al., 2015). One challenge in using these strategies is the potential trade-off between high yield and biodiversity and soil preservation (e.g., Pittelkow et al., 2015), which was also evidenced here by the reduction in yield in the no-tillage treatment compared with plowed spring wheat. However, the results showed that using crop rotation in no-tillage systems can help to solve this problem, at least partly.

CONCLUSIONS

Long-term experiments are valuable for assessing the impacts of crop rotation cycle on production and environmental benefits, as well as potential constraints from diversification. Such information is essential when designing more resilient cropping systems for northern agriculture. Based on our results, there are yield gains from diverse crop rotations that include cereals, oilseeds, and legumes in northern spring wheat production, with the magnitude being larger in reduced tillage systems. Assessing the yield quantity and quality, presence of weeds, plant diseases and insect pests as a whole, can contribute to understanding aspects of temporal diversification on cropping system performance in the long run. To get the best output from crop diversification in cereal production, particular attention should be paid to the health of each plant species in the crop rotation, especially if the pest control effects of the soil tillage are excluded.

REFERENCES

Altieri, M. A., Nicholls, C. I., Henao, A., and Lana, M. A. (2015). Agroecology and the design of climate change -resilient farming systems. *Agron. Sustain. Dev.* 35, 869–890. doi: 10.1007/s13593-015-0285-2

Andersen, A. (1999). Plant protection in spring cereal production with reduced tillage. II. Pests and beneficial insects. *Crop. Prot.* 18, 651–657. doi: 10.1016/S0261-2194(99)00071-X

Babublicová, M. (2016). Enhancing of winter wheat productivity by the introduction of field pea into crop rotation. *Agriculture* 62, 101–110. doi: 10.1515/agri-2016-0011

Bailey, K. L., Gossen, B. D., Lafond, G. P., Watson, P. R., and Derksen, D. A. (2001). Effect of tillage and crop rotation on root and foliar diseases of wheat and pea in Saskatchewan from 1991 to 1998: univariate and multivariate analyses. *Can. J. Plant Sci.* 81, 789–803. doi: 10.4141/P00-152

Bárberi, P., and Cascio, B. L. (2001). Long-term tillage and crop rotation effects on weed seedbank size and composition. *Weed Res.* 41, 325–340. doi: 10.1046/j.1365-3180.2001.00241.x

Berzsenyi, Z., and Gyorffy, B. (1997). Effect of crop-rotation and fertilization on maize and wheat yields and yield stability in a long-term experiment. *Eur. J. Agron.* 13, 223–244. doi: 10.1016/S1161-0301(00)00076-9

Bleiholder, H., Feller, C., Hess, M., Meter, U., van den Boom, T., Lancashire, P. D., et al. (1997). *Compendium of Growth Stage Identification Keys for Monocotyledonous and Dicotyledonous Plants-Extended BBCH Scale*, eds M. Enz and Ch. Dachler. Novartis.

Bockus, W. W. (1992). Effects of crop rotation and residue management practices on severity of tan spot of winter wheat. *Plant Dis.* 76, 633–636. doi: 10.1094/PD-76-0633

Bommarco, R., Kleijn, D., and Potts, S. G. (2013). Ecological intensification: harnessing ecosystem services for food security. *Trends Ecol. Evol.* 28, 230–238. doi: 10.1016/j.tree.2012.10.012

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

LJ, EH, and HJ designed the experiment. MJ, EH, and HJ conducted the experiments and contributed to field data collections. LJ and MN analyzed the data. All authors prepared the manuscript, participated in the writing process, and approved the manuscript before its submission.

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SUPPLEMENTARY MATERIAL

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Bullock, D. G. (1992). Crop rotation. *Crit. Rev. Plant. Sci.* 11, 309–326. doi: 10.1080/07352689209382349

Chamanab, H. R. M., Ghorbani, A., Ashghi, A., Tulikov, A. M., and Zargarzadeh, F. (2009). Long-term effects of crop rotation and fertilizers on weed community in spring barley. *Tark. J. Agric.* For. 33, 315–323. doi: 10.3906/tjaf-0904-31

Chen, X. Y., and Heenan, D. P. (1996). The influence of crop rotation on soil structure and soil physical properties under conventional tillage. *Soil Tillage Res.* 37, 113–125. doi: 10.1016/0167-1987(96)00108-2

Chandler, L. D., and Faust, R. M. (1998). Overview of area-wide management of insects. *J. Agric. Urban Entomol.* 15, 319–325.

Coaker, T. H. (1987). "Cultural methods: the crop," in Integrated Pest Management, eds A. J. Burn, T. J. Coaker, and P. C. Jepson (London: Academic Press), 69–88.

Delin, S., Nyberg, A., Lindén, B., Ferm, M., Torstensson, G., Lerenius, C., et al. (2008). Impact of crop protection on nitrogen utilisation and losses in winter wheat production. *Eur. J. Agron.* 28, 361–370. doi: 10.1016/j.eja.2007.11.002

Di, H. J., and Cameron, K. C. (2002). Nitratre leaching in temperate agroecosystems: sources, factors and mitigating strategies. *Nutr. Cycling Agroecosyst.* 46, 237–256. doi: 10.1023/A:10214715131188

Duru, M., Therond, O., Martin, G., Martin-Clouaire, R., Magne, M. A., Delin, S., Nyberg, A., Lindén, B., Ferm, M., Torstensson, G., Lerenius, C., et al. (2008). Impact of crop protection on nitrogen utilisation and losses in winter wheat production. *Eur. J. Agron.* 28, 361–370. doi: 10.1016/j.eja.2007.11.002

Jørgensen, L. N., and Olsen, L. V. (2007). Control of tan spot (*Puccinia graminis* Tranzschel) on wheat in Denmark. *Phytopathology* 97, 573–578. doi: 10.1094/PHYTO-97-0573

Kayed, Y., Müller, J., and Iselstein, J. (2010). Nitrogen management in organic farming: comparison of crop rotation residual effects on yield, N leaching and soil conditions. *Nutr. Cycl. Agroecosyst.* 87, 21–31. doi: 10.1007/s10705-009-9309-0

Keesing, F., Belden, L. K., Dascz, P., Dobson, A., Harvell, D. H., Holt, R. D., et al. (2010). Impacts of biodiversity on the emergence and transmission of infectious diseases. *Nature* 468, 647–652. doi: 10.1038/nature09575

Kennedy, G. G., and Husted, A. S. (2010). Pest pressure relates to similarity of crops and native plants. *Proc. Natl. Acad. Sci. U. S. A.* 117:945117. doi: 10.1073/pnas.200945117

Klein Haneyveld, W. K., and Stegeman, A. W. (2005). Crop succession requirements in agricultural production planning. *Eur. J. Oper. Res.* 166, 406–429. doi: 10.1016/ejor.2004.03.009

Krupinsky, J. M., Bailey, K. L., McMullen, M. P., Gossen, B. D., and Turkington, T. K. (2002). Managing plant disease risk in diversified cropping systems. *Agron. J.* 94, 198–209. doi: 10.2134/agronj2002.0198

Kurppa, S. (1990). *Insect Pest Damage, Predicting and Control in Finnish Cereal Cultivation During 1980s.* (PhD Thesis). Faculty of Agriculture and Forestry, University of Helsinki, Helsinki, Finland.

Légère, A., and Stevenson, E. C. (2002). Residual effects of crop rotation and weed management on a wheat test crop and weeds. *Weed Sci.* 50, 101–111. doi: 10.1614/0043-1745(2002)050[01002:REOCR]2.0.CO;2

Liebman, M., and Dyck, E. (1993). Crop rotation and intercropping strategies for weed management. *Ecol. Appl.* 3, 92–122. doi: 10.2307/1941795

López-Bellido, L., López-Bellido, R., Castillo, J., and López-Bellido, F. (2001). Effects of long-term tillage, crop rotation and nitrogen fertilization on bread-making quality of hard red spring wheat. *Field Crops Res.* 72, 197–210. doi: 10.1016/S0378-4290(01)00177-0

Luke (2020a). *Official Statistics of Finland (OSF): Utilised Agricultural Area.* Helsinki: Natural Resources Institute Finland. Available online at https://stat. luke.fi/en/utilised-agricultural-area (accessed November 21, 2020).

Luke (2020b). *Official Statistics of Finland (OSF): Feed Tables.* Helsinki: Natural Resources Institute Finland. Available online at https://portal.mtt.fi/portal/ page/port/rehutaulukot/feed_tables_en (accessed November 26, 2020).

Luke (2020c). *Official Statistics of Finland (OSF): Yield of the Main Crop.* Helsinki: Natural Resources Institute Finland. Available at http://statdb.luke. fi/PXWeb/pxweb/en/LUKE/FO_02%20Maatalous_04%20Tuotanto__ 14%20Satotilasto/01_Viljelykasvien_sato.px/table/tableViewLayout1/?rxid= 69c91bf6-f37a-4386-97bb-3c51b8782811 (accessed November 16, 2020).

Malhi, S. S., and Lemke, R. (2007). Tillage, crop residue and N fertilizer effects on crop yield, nutrient uptake, soil quality and nitrous oxide gas emissions in a second 4-yr rotation cycle. *Soil Tillage Res.* 96, 269–283. doi: 10.1016/j.still.2007.06.011

Mamolos, A. P., and Kalburtji, K. L. (2001). Significance of alleyophy in crop rotation. *J. Crop Prod.* 4, 197–218. doi: 10.1300/J140v04n02_06

Meisinger, J. J., and Delgado, J. A. (2002). Principles for managing nitrogen leaching. *J. Soil Water Conserv.* 57, 485–498. Available online at: https://www. jswconline.org/content/jswc/57/4/585.full.pdf

Mertens, S. K., van den Bosch, F., and Heesterbeek, J. A. P. (2002). Weed populations and crop rotations: exploring dynamics of a structured periodic system. *Ecol. Appl.* 12, 1125–1148. doi: 10.1890/1571-0676(2002)012[1125:WPACR]2.0.CO;2

Metzger, M. J., Bunce, R. G. H., Jongman, R. H. G., Muche, C. A., and Watkins, J. W. (2005). A climatic stratification of the environment of Europe. *Global Ecol. Biogeogr.* 14, 549–563. doi: 10.1111/j.1466-822X.2005.00190.x

Offert, O. O., Muerjeri, M. K., and Doane, J. F. (1985). Relationship between infestations levels and yield loss caused by wheat midge, *Stomodiplosis mosellana* (Géhin) (Diptera: Cecidomyiidae), in spring wheat in Saskatchewan. *Can. Entomol.* 117, 593–598. doi: 10.4039/Ent117593-5

Palojärvi, A., Kellock, M., Parikka, P., Jauhiainen, L., and Alakukku, L. (2020). Tillage system and crop sequence affect soil disease suppressiveness
and carbon status in Boreal climate. *Front. Microbiol.* 2020;534786. doi: 10.3389/fmicb.2020.534786

Paulitz, T. C. (2006). Low input no-till production in the Pacific Northwest of the U.S.: the challenges of root diseases. *Eur. J. Plant Pathol.* 115, 271–281. doi: 10.1007/s10658-006-9023-6

Paulitz, T. C., Schroeder, K. L., and Schüllinger, W. F. (2010). Soilborne pathogens of cereals in an irrigated cropping system: effects of tillage, residue management, and crop Rotation. *Plant Dis.* 94, 61–68. doi: 10.1094/PDIS-94-1-0061

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., and Smith, P. (2016). *Nature* 532, 49–57. doi: 10.1038/nature17174

Peltonen-Sainio, P. (2012). “Crop production in a northern climate,” in *Field Crops Res.*

Peltonen-Sainio, P., Kangas, A., Salo, Y., and Jauhiainen, L. (2007). *Field Crops Res.*

Peltonen-Sainio, P., Jauhiainen, L., Honkavaara, E., Wittke, S., Karjalainen, M., Hyvönen, T., and Jalli, H. (2011). Composition of weed flora in spring cereals in Finland - a fourth survey. *Agric. Food Sci.* 20, 245–261. doi: 10.21371/145960611797471534

Pittelkow, C. M., Liang, X., Linquist, B. A., van Groenigen, K. J., Lee, J., Lundy, M. E., et al. (2015). Productivity limits and potentials of the principles of conservation agriculture. *Nature* 517, 365–368. doi: 10.1038/nature13809

Rajala, A., Hakala, K., Mäkelä, P., Muurinen, S., and Peltonen-Sainio, P. (2009). Spring wheat response to timing of water deficit through sink and grain filling capacity. *Field Crops Res.* 114, 263–271. doi: 10.1016/j.fcr.2009.08.007

Ratnadass, A., Fernandes, P., Avelino, J., and Habib, R. (2012). Crop diversity for sustainable management of crop pests and diseases in agroecosystems: a review. *Agron. Sustain. Dev.* 32, 273–303. doi: 10.1007/s13593-011-0022-4

Salonen, J., Hyvönen, T., and Jalli, H. (2011). Composition of weed flora in spring cereals in Finland - a fourth survey. *Agric. Food Sci.* 20, 245–261. doi: 10.21371/145960611797471534

Sexton, D. L., and Wyman, J. A. (2005). Effect of crop rotation distance in populations of Colorado potato beetle (Coleoptera: Chrysomelidae): development of area wide Colorado potato beetle pest management strategies. *J. Econ. Entomol.* 98, 716–724. doi: 10.1603/0222-0493-98.3.716

Sieling, K., and Christen, O. (2015). Crop rotation effects on yield of oilseed rape, wheat and barley and residual effects on the subsequent wheat. *Arch. Agron. Soil Sci.* 61, 1531–1549. doi: 10.1007/s00126-015-07569

Sieling, K., Stahl, C., Winkelmann, C., and Christen, O. (2005). Growth and yield of winter wheat in the first 3 years of a monoculture under varying N fertilization in NW Germany. *Eur. J. Agron.* 22, 71–84. doi: 10.1016/j.eja.2003.12.004

Skellern, M. P., and Cook, S. M. (2018). The potential of crop management practices to reduce pollen beetle damage in oilseed rape. *Arthropod Plant Interact.* 12, 867–879. doi: 10.1007/s11295-017-9571-z

Smith, R. G., Gross, K. L., and Robertson, G. P. (2008). Effects of crop diversity on agroecosystem function: crop yield response. *Ecosystems* 11, 355–366. doi: 10.1007/s10021-008-9124-5

Soon, Y. K., and Clayton, G. W. (2002). Eight years of crop rotation and tillage effects on crop production and N fertilizer use. *Can. J. Soil Sci.* 82, 165–172. doi: 10.4141/001-047

Stevenson, F. C., and van Kessel, C. (1996). The nitrogen and non-nitrogen rotation benefits of pea to succeeding crops. *Can. J. Plant Sci.* 76, 735–745. doi: 10.4141/cips96-126

Stinner, B. R., and House, G. J. (1990). Arthropods and other invertebrates in conservation-tillage agriculture. *Annu. Rev. Entomol.* 35, 299–318. doi: 10.1146/annurev.en.35.010190.001503

Tamburini, G., Bommarco, R., Wanger, T. C., Kremen, C., van der Heijden, M. G. A., Liebman, M., et al. (2020). Agricultural diversification promotes multiple ecosystem services without compromising yield. *Sci. Adv.* 6:aba1715. doi: 10.1126/sciadv.abab1715

Trnka, M., Olesen, J. E., Kerselbaum, K. C., Skjelvåg, A. O., Eitzinger, J., Seguin, B., et al. (2011). Agroclimatic conditions in Europe under climate change. *Glob. Change Biol.* 17, 2298–2318. doi: 10.1111/j.1365-2486.2011.02396.x

Tuutola, E., Salo, T., Miettinen, A., Iho, A., Valkama, E., Rankinen, K., et al. (2017). *Hyötylä taseista-Ravinnetaseiden tulkinna ympäristön ja viljelyn hyödyksi. Luonnonnovaara- ja biotolouden tutkimus 15/2017. Helsinki: Luonnontuvarakeskus.

Uusitalo, R., Närvänäinen, A., Kaseva, A., Launto-Tiutti, A., Heikkilä, J., Joki-Hieskala, P., et al. (2015). Conversion of dissolved phosphorus in runoff by ferric sulfate to a form less available to algae: field performance and cost assessment. *AMBIO* 44, 286–296. doi: 10.1007/s13280-014-0622-8

Vasileiadis, V. P., Sattin, M., Otto, S., Veres, A., Pálinkás, Z., Ban, R., et al. (2011). Crop protection in European maize-based cropping systems: current practices and recommendations for innovative Integrated Pest Management. *Agric. Syst.* 104, 533–540. doi: 10.1016/j.agsy.2011.04.002

Venkatesh, M. S., Hazra, K. K., Ghosh, P. K., Khuswah, B. L., Ganeshamurthy, A. N., Ali, M., et al. (2017). Long-term effect of crop rotation and nutrient management on soil–plant nutrient cycling and nutrient budgeting in Indo-Gangetic plains of India. *Agric. Agron. Soil Sci.* 63, 2007–2022. doi: 10.1080/03650340.2017.1320392

Wang, H., Guo, Z., Shi, Y., Zhang, Y., and Yu, Z. (2015). Impact of tillage practices on nitrogen accumulation and translocation in wheat and soil nitrate-nitrogen leaching in drylands. *Soil Tillage Res.* 153, 20–27. doi: 10.1016/j.still.2015.03.006

Wozniak, A. (2019). Effect of crop rotation and cereal monoculture on the yield and quality of winter wheat grain and on crop infestation with weeds and soil properties. *Int. J. Plant Prod.* 13, 177–182. doi: 10.1007/s42106-019-00044-w

Wozniak, A. (2020). Effect of cereal monoculture and tillage systems on grain yield and weed infestation of winter durum wheat. *Int. J. Plant Prod.* 14, 1–8. doi: 10.4210/ijpp.2019-019-00062-8

Zawislak, K., and Kostrzewska, M. K. (2005). Nutrients competition of weeds with winter wheat stands grown in crop rotation and long-term monoculture. P.I. Density and floristic composition of weeds communities. *Ann. Univ. Mariae Curie Sklodowska, Sectio E Agricultura* 55, 245–251.

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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