Acta Agriculturae Scandinavica, Section B — Soil & Plant Science

ISSN: 0906-4710 (Print) 1651-1913 (Online) Journal homepage: https://www.tandfonline.com/loi/sagb20

Influence of mechanical weeding and fertilisation on perennial weeds, fungal diseases, soil structure and crop yield in organic spring cereals

Lars Olav Brandsæter, Kjell Mangerud, Lars Andersson, Trond Børresen, Guro Brodal & Bo Melander

To cite this article: Lars Olav Brandsæter, Kjell Mangerud, Lars Andersson, Trond Børresen, Guro Brodal & Bo Melander (2020) Influence of mechanical weeding and fertilisation on perennial weeds, fungal diseases, soil structure and crop yield in organic spring cereals, Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 70:4, 318-332, DOI: 10.1080/09064710.2020.1728371

To link to this article: https://doi.org/10.1080/09064710.2020.1728371

ACTA AGRICULTURAE SCANDINAVICA, SECTION B — SOIL & PLANT SCIENCE
2020, VOL. 70, NO. 4, 318–332
https://doi.org/10.1080/09064710.2020.1728371

Influence of mechanical weeding and fertilisation on perennial weeds, fungal diseases, soil structure and crop yield in organic spring cereals

Lars Olav Brandsæter[a,b], Kjell Mangerud[b], Lars Andersson[c], Trond Børresen[d], Guro Brodal[b] and Bo Melander[e]

[a]Norwegian University of Life Sciences (NMBU), Faculty of Biosciences, Department of Plant Sciences, Ås, Norway; [b]Norwegian Institute of Bioeconomy Research (NIBIO), Division of Biotechnology and Plant Health, Ås, Norway; [c]Department of Crop Production Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden; [d]Norwegian University of Life Sciences (NMBU), Faculty of Environmental Sciences and Natural Resource Management (MINA), Ås, Norway; [e]Aarhus University, Faculty of Technical Sciences, Department of Agroecology, Research Centre Flakkebjerg, Slagelse, Denmark

ABSTRACT

There is a need both in organic farming and on farms using integrated pest management for non-chemical measures that control the perennial weed flora. The effect of mechanical weeding and fertilisation on perennial weeds, fungal diseases and soil structure were evaluated in two different experiments in spring cereals. Experiment I included six strategies. The first strategy was (1) without specific measures against perennial weeds. The other strategies encompassed one or two seasonal control measures; (2) rhizome/root cutting with minimal soil disturbance in autumn, (3) hoeing with 24 cm row spacing, (4) combined hoeing and disc harrowing in autumn, (5) 'KvikUp' harrowing in spring, and (6) 'KvikUp' harrowing in spring and autumn. Experiment II included factor (i) inter-row hoeing and (ii) fertilisation level. This experiment included the comparison between normal row spacing (12 cm) with weed harrowing versus double row spacing (=24 cm) in combination with inter-row hoeing and 4 fertilisation levels (50–200 kg N ha^{-1}). In experiment I the strategies consisting of no or one direct weed control measure (1, 2, 3 and 5) clearly did not control the perennial weeds. The two seasonal control measures (4 and 6) gave a satisfactory weed control and highest crop yield. The combination of best weed control and no measured harmful effects on soil structure or increase of fungal diseases may explain the highest yields for these strategies. In Experiment II, hoeing and 24 cm spacing gave less perennial biomass compared to 12 cm spacing. Grain yields increased linearly with increasing nitrogen input. The study shows that both inter-row hoeing and weed harrows, are important elements in integrated pest management practice and organic farming. In addition, our results indicate that efficient mechanical weeding is possible without harmful effects in crop rotation consisting of various spring cereals as regards soil structure and plant health.

ARTICLE HISTORY
Received 3 April 2019
Accepted 6 February 2020

KEYWORDS
Weed control; *Cirsium arvense*; *Elymus repens*; *Sonchus arvensis*; *Stachys palustris*; *Vicia cracca*; soil tillage; row spacing

Introduction

Organic cereal production in Norway is partly performed in areas with a low density of animal husbandry infrastructure. Both research and practical experience have shown that organic cereal production without or with very limited use of animal manure (e.g. farmyard manure) returns low yields with large year-to-year variation (Korsaeth and Eltun 2008). Including a full-season green manure cover crop (usually a legume-grass mix) has been common in such cropping systems as part of the crop rotation aiming at both nitrogen supply and weed control effects. Frequent mowing throughout the summer of a full-season green cover-crop manure did for instance control creeping thistle (*Cirsium arvense)* in succeeding cereal crops (Dock-Gustavsson 1997; Graglia et al. 2006; Thomsen et al. 2015). Other weed species such as couch grass (*Elymus repens)*, however, may be poorly controlled in such cover crops (Vanhala et al. 2006; Thomsen et al. 2015; Melander et al. 2016). Moreover, there are also concerns both regarding weeds, especially some perennial creeping species as *E. repens* (Thomsen et al. 2015), mineralisation and leakage of nitrogen outside of the growing season (Korsaeth and Eltun 2008). The need for additional sources of fertilisation under such circumstances may be met by the utilisation of different organic waste sources, such as biogas residue and commercially available livestock manure, e.g. as pelletised, dried chicken manure (Frøseth et al. 2014). Another

CONTACT Lars Olav Brandsæter lars.olav.brandsaeter@nmbu.no Norwegian University of Life Sciences (NMBU), Faculty of Biosciences, Department of Plant Sciences, P.O. Box 5003, NO-1432 Ås, Norway; Norwegian Institute of Bioeconomy Research (NIBIO), Division of Biotechnology and Plant Health, P.O. Box 115, NO-1431 Ås, Norway

Supplemental data for this article can be accessed https://doi.org/10.1080/09064710.2020.1728371

significant drawback of full-season green manure crops is that these prevent the growing of a cash crop.

In organic cereal cropping systems, with or without a whole year cover-crop, perennial weeds such as *C. arvense*, *Sonchus arvensis* (perennial sow-thistle) and *E. repens* are of great concern in many temperate countries (Cormack 1999; Salonen et al. 2001; Melander et al. 2012). Researchers and farmers claim that perennial creeping weeds threaten the future of organic cereal production, unless the management of these weeds is given due consideration in crop rotation (Salonen et al. 2001; Sundheim et al. 2014). Not least, there is a need for measures that control the whole weed flora efficiently in a multiyear perspective. These measures must be so robust that single years with difficult conditions, for example moist autumns, for mechanical weed control not cause unacceptable weed pressure. It is a challenge to find measures that are effective against all species of perennial weeds simultaneously. For example, studies by Permin (1961) and Brandsæter et al. (2012) showed that stubble soil cultivation in autumn is more effective against *E. repens* than against *C. arvense* and *S. arvensis*. Recent studies by Brandsæter et al. (2017) show that the latter two species are more vulnerable to disturbance in spring compared to autumn. One obstacle, however, is that traditional harrow types like disc-harrows need a rather long period, maybe 3–4 weeks, in spring for sufficient weed control, and that causes late sowing of the crop and lower crop yield, at least at northern latitudes (Brandsæter et al. 2017). Melander et al. (2012) demonstrated that early post-harvest control strategies based on rotating weeding devices and mouldboard ploughing conducted in consecutive years was effective against mixed stands of perennials. However, such intensive autumn tillage may not enable optimal nutrient management on organic farms and thus only relevant against severe perennial weed problems. Recently developed mechanical implements, such as the 'KVIK-UP' harrow, may have the potential for shortening the cultivation period. Numerous farmers throughout Scandinavia claim to have good experiences with such equipment. Most experiments with such harrows have, however, been conducted in autumn.

Earlier studies by Thomsen et al. (2015) and Melander et al. (2016) indicate that periods of soil cultivation, for example both in the autumn and in spring, may be required for controlling mixed stands of perennial weeds in cereal-dominated rotations, but there is a need to verify this with new studies. Furthermore, considerations to the total sustainability of the system are required. Solutions that, e.g. result in more diseases and poorer soil structure are not desirable. Organic cereal crops are vulnerable to foliar disease infections (Van Bruggen and Finckh 2016), and more information is needed about the possible influence of different stubble and soil cultivation operations, row spacing, fertilisation levels and living mulch on foliar cereal diseases under Norwegian conditions.

Regarding soil structure, Njøs and Børresen (1991) found that stubble cultivation in combination with spring or autumn ploughing influenced aggregate stability negatively in two of three experimental years. In a long-term field experiment, Fahnbulleh (2014) found the same negative trend on aggregate stability for the combination stubble cultivation and autumn ploughing, but for spring ploughing the effect of stubble cultivation was positive. However, both Fahnbulleh (2014) and Marti (1984) reported that penetration resistance in the ploughed layer increased after stubble cultivation. Results from a study in Sweden on clay soil (Myrbeck et al. 2012) concluded that delaying ploughing in autumn and omitting stubble cultivation had a small effect on soil mineral nitrogen contents, but had a long-term negative effect on grain yields and soil structure. The effect of stubble cultivation in autumn in combination with ploughing in autumn or spring on soil structure seems to be small, but there is insufficient knowledge about stubble cultivation in spring before ploughing.

An obvious measure for increasing crop yields in organic farming is to increase the fertilisation level, but an unwanted consequence can be increased problems with weeds and diseases. Fertilisation level may influence the weed species differently, e.g. some will be stimulated. Furthermore, effects of nutrient supply on perennial weeds may interact with the choice of soil tillage, and such interactions may differ between weed species (Håkansson 2003). Higher fertilisation level and a denser crop canopy might contribute to disease development (Burdon and Chilvers 1982; Lemmens et al. 2004; Walters and Bingham 2007; Askegaard et al. 2011), although no or variable effects of N on diseases have also been reported (Walters and Bingham 2007; Salgado et al. 2017). If increased fertilisation gives increased problems with weeds and diseases, the solution may be to combine hoeing and increased row distance. This provides opportunities for both in-crop weed control and a more open crop canopy. It seems that organically grown spring cereals do not yield less when widening the inter-row spacing up to 30 cm (Melander et al. 2018).

The aim of this study was to explore the effects of the use of stubble cultivation in autumn and/or soil cultivation in spring (off-crop), mechanical weed control (in-crop) by hoeing combined with increased row distance and fertilisation levels on weed infestation, fungal diseases, soil structure and crop yield.

Material and methods

The study consisted of two field experiments, both running for 3 years, designated Experiment I and Experiment II.

Study site, experimental design and treatments

The experiments were located at the Norwegian University of Life Sciences (NMBU), Ås (59°40′N, 10°47′E, 75 metres above sea level). The soil is described as silty clay loam with poor natural drainage (Bakken et al. 2006) and classified as Epistagnic Albeluvisol (Siltic) (World Reference Base 2006). Prior to the experiments, both fields had been farmed organically for a number of years, mainly with crop rotations dominated with cereal crops (with and without undersown clover) and with green manure (clover-grass mixture) every fourth year. All experimental plots were mouldboard ploughed (ploughing depth 23–25 cm) in spring with a reversible mouldboard plough (Kverneland with body no.8) equipped with disc-coulters and skimmers. The soil was then levelled (with a separate under-beam leveller Type Väderstad) before all plots were fertilised with dried chicken manure ['Marihøne Pluss' 8 (%N) – 4 (%P) – 5 (%K)] corresponding to 100 kg total N ha^{-1} in experiment I (except strategy 2 that received 50 kg N ha^{-1} the first experimental year) and 50–200 kg N ha^{-1} in experiment II. The manure was broadcasted by a tractor propelled fertiliser spreader (Kverneland Villemo, Norway). Immediately after fertilisation, the experimental area was harrowed with a s-tine cultivator (type Väderstad NZM 400) for seed bed preparation. The plots were sown with a seed drill (type Nordsten 2.5 m). Spring barley cv. Brage (200 kg ha^{-1}, equivalent to 542 kernels m^{-2} in 2013 and 521 kernels m^{-2} in 2014) was sown both in 2013 (Experiment II) and in 2014 (Experiments I and II), with oat cv. Hurdal (200 kg ha^{-1}, equivalent to 526 kernels m^{-2}) in 2015 (Experiments I and II) and with spring wheat cv. Mirakel (225 kg ha^{-1}, equivalent to 551 kernels m^{-2}) in 2016 (Experiment I). The same seed drill was used for both normal row distance (12 cm) and double spaced (24 cm), for the latter every second seeding unit was closed. The same seed rate per ha was used for both row distances. After sowing, all plots were rolled with a Cambridge roller.

Experimental description

The timing of management operations and weed assessments in the experiments is presented in Table 1. Both experiments were designed as randomised block experiments. Individual plot size was 7.5 by 10 m, and each treatment had four (experiment I) or three (experiment II) replications. There were headlands of 15 m width between replicates for turning the tractor and implements. Treatments were repeated on the same plots for 3 years, 2013–2016 (experiment I) and 2013–2015 (experiment II).

Experiment I, 2013–2016

In this experiment, we studied the effect of six different strategies, where different actual measures are added to a control treatment, for control of perennial weeds

Table 1. Dates for management and assessment operations in the two experiments (I and II). Number behind operation is strategy number (see Table 2).

		2013	2014	2015	2016
I	KVIK-UP harrowing: 5,6		23 April	21 April	28 April
	Ploughing: 1,2,3,4,		24 April	22 April	28 April
	Ploughing all plots	8 May			
	Levelling:1,2,3,4	20 May	26 April	22 April	7 May
	Fertilizing: 1,2,3,4	20 May	29 April	23 April	7 May
	Seedbed preparation: 1,2,3,4	20 May	29 April	23 April	8 May
	Sowing cereals: 1,2,3,4	21 May	30 April	24 April	8 May
	Rolling: 1,2,3,4		30 April	24 April	8 May
	Ploughing: 5,6		28 April	24 April	10 May
	Levelling: 5,6		29 April	24 April	10 May
	Fertilizing: 5,6		29 April	24 April	11 May
	Seedbed preparation: 5,6		29 April	24 April	11 May
	Sowing cereals: 5,6		30 April	24 April	11 May
	Rolling: 5,6		30 April	24 April	11 May
	Sowing white clover: 2	26 May	21 May	10 June	16 June
	Weed harrowing (I): 1,2,5,6		22 May	–	–
	Weed harrowing (II): 1,2,5,6		–	–	–
	Hoeing (I): 3,4		10 June	27 May	2 June
	Hoeing (II): 3,4		–	10 June	17 June
	Hoeing (III): 3,4		–	23 June	–
	Grain harvesting	22 Aug	15 Aug	7 Sept	10 Sept
	Perennial weed assessment	23–27 Aug	18–19 Aug	8–10 Sept	12–16 Sept
	Cutting stubble (I): 1,2,3,5,	28 Aug	28 Aug	11 Sept	
	KVIK-UP harrowing (I):6	29 Aug [a]	28 Aug	11 Sept	
	Disc harrowing (I): 4	29 Aug [a]	28 Aug	11 Sept	
	Rhizome/root cutter: 2	29 Aug [b]	3 Sept [b]	11 Sept [b]	
	Cutting stubble (II): 1,2,3,5	26 Sept	23 Sept	–	
	KVIK-UP harrowing (II): 6	26 Sept	24 Sept	–	
	Disc harrowing (II): 4	26 Sept	24 Sept	–	
II	Ploughing all plots	26 May	24 April	21 April	
	Levelling	26 May	26 April	22 April	
	Fertilizing	26 May	29 April	23 April	
	Seedbed preparation	26 May	29 April	23 April	
	Sowing cereals	26 May	30 April	24 April	
	Rolling	27 May	30 April	24 April	
	Weed harrowing (I)	1 June	22 May	–	
	Weed harrowing (II)	17 June	–	–	
	Hoeing (I)	17 June	10 June	27 May	
	Hoeing (II)	3 July	–	10 June	
	Hoeing (III)	–	–	23 June	
	Grain harvesting	2 Sept	15 Aug	7 Sept	
	Perennial weed assessment	28 Aug	27– 29 Aug	28 Aug–1 Sept	

[a]Two treatment the same day, dry and hard soil. [b]'Kverneland Vertical cutter' in 2013 and 2014, 'Kverneland Horizontal cutter' in 2015.

on weed growth, fungal crop diseases, soil structure and spring cereal yield. The six different weed control strategies were combinations of harrowing (with/without) in spring, hoeing (with/without) in the cereal crop and different stubble cultivation treatments in autumn (Table 2). The six strategies consisted of four strategies (1–4) without a harrowing period in spring and strategy 5 and 6 with. Strategy #1 was without any specific measures for control of perennial weeds except mowing the stubble and the weeds just after harvest. For three of the other strategies, one additional measure against perennial weeds was added, strategy (i) #2 included a clover living mulch combined with below-ground fragmentation of shallow growing rhizomes and roots in the autumn, (ii) #3 with inter-row hoeing and (iii) #5 included a KvikUp-harrowing period in spring. #4 was similar to #3 but a period of disc harrowing in autumn was added. #6 was an intensive version of #5 with KvikUp-harrowing periods in spring and autumn.

The experiment was initiated in autumn 2013 and continued until August 2016. The treatments started with stubble cultivation or mowing after crop harvest in 2013 (Tables 1–3). The stubble cultivation treatments were, with few exceptions (Table 1), repeated twice during autumn.

Experiment II, 2013–2015

In this experiment two of the strategies included in Experiment I, #1 and #3, was studied for effects of double row distance in combination with inter-row hoeing, versus single row distance, and fertilisation level on weed growth, fungal crop diseases and spring cereal yield. The experimental treatments were inter-row hoeing, *with* (row spacing 24 cm) and *without* (row spacing 12 cm). There were equal number of crop plants m^{-2} for both row distances and fertilisation level (corresponding to 50, 100, 150 and 200 kg total N ha^{-1}) combined in a factorial split-plot design with hoeing allotted to main plots and fertilisation to subplots. The experiment was initiated in spring 2013 and continued until August 2015 (Table 1).

Table 2. Description of the six different strategies (#) for control of perennial weeds in Experiment I.

#	Spring: Harrowing period[a] No	Spring: Harrowing period[a] Yes	Summer: Hoeing[b] No	Summer: Hoeing[b] Yes	Autumn: Stubble cultivation
1	x		x		Mowing
2[c]	x		x		'Vertical –cutter' + Mowing
3	x			x	Mowing
4	x			x	'Disc' harrowing
5		x	x		Mowing
6		x	x		'KVIK-UP' harrowing

[a]'No'; early (normal) sowing date in spring. 'Yes'; the use of a 'KVIK-UP'-harrow and delayed time of sowing spring cereals (see Table 1). [b] 'No'; normal row spacing (12 cm). 'Yes'; double spacing (24 cm) and hoeing between. [c] Undersown white clover.

Assessments

Weed and crop assessments

Weed shoot density and aboveground weed biomass per species and crop biomass were assessed before harvest (Table 1) in four randomly placed (first experimental year) 1 m^2 quadrats per plot each year. The assessed quadrats were placed in exactly the same position every year. Before initiating the experiments (Exp. I August 2013; Exp. II August 2012), shoot density per species was assessed in the same four quadrates as in later years. Plants were cut 5 cm above the soil surface, simulating cutting at crop harvest. The biomass samples were dried at 70 °C for 72 h to determine the dry weight. All data were calculated to density (shoots m^{-2}) and aboveground dry matter (DM) (g m^{-2}) before statistical analysis.

Weed infestation in Exp. 1 was also estimated visually all years at the growth stages BBCH 85–90. The space occupied by the crop and the most abundant weed species, and less frequent species together as 'other species', on all subplots was expressed as percentage ground coverage. The area covered by crop, weed species and bare soil was summed to 100%.

The crop was harvested by a plot harvester just outside the areas in which the weeds were recorded. The harvested areas were 1.5 m wide and 9–10 m long, the exact length was measured in each case.

Fungal disease assessments

Fungal diseases were assessed visually once or twice during each growing season. However, because only few symptoms were observed at growth stage BBCH 20–30 (tillering), BBCH 40–55 (from booting to heading), and BBCH 65 (flowering), and since no obvious differences between experimental treatments could be seen, no systematic recordings were made. However, to get a general indication of the disease infestation each year, the percentage of plants showing symptoms of the foliar diseases barley net blotch (*Pyrenophora teres*), oat leaf spot (*Pyrenophora avenae*) and wheat leaf spot complex (*Parastagonopora nodorum*, *Zymoseptoria tritici*, *Pyrenophora tritici-repentis*) were recorded in 4 × 1 m rows in two or three randomly selected plots in each experiment each year at BBCH 20–30. In 2015, three randomly selected plots (oats) were also assessed at BBCH 65, as described above.

Representative samples of harvested grains from each treatment and replicate each year in Experiment I, and

Table 3. Implements and settings used in experiments I and II.

Experiment	Trade mark (Brand?)	Tilling (stubble) device	Working depths (cm)	PTO r min^{-1}	Forward speed (km h^{-1})
I and II	Hatzenbichler Interrow cultivator (2.4 m)	Goosefoot shares, 18 cm More information on: http://www.hatzenbichler.com/hatzenbichler/en/products.html	2–4	–	3–4
I and II	Einböch spring tine harrow (4.5 m)	More information on: http://www.einboeck.at/index.php?option=com_content&view=article&id=2050&Itemid=891&lang=en	2	–	8–10
I	KVIK-UP-harrow	Heavy tines, with goosefoot shares, loosens the soil in ca 15 cm depth. Rotor with spring tines. Throws soil and plant material up- and backwards. Speed 180 r min^{-1} (powered by tractor PTO), The spring tines works in 5–7 cm. depth. More information on: http://www.kvikagro.com/en_ku_info.html	15 (goosefoot) /5 (spring tines)	480	4–5
I	Disc-harrow	Disc diameter 35 cm. Kverneland, Norway.	8–10	–	8–10
I and II	Kverneland FH180 Chopper	Stubble and pasture mower. http://no.kverneland.com/Grasprodukter/Beitepussere	4–6 [a]	540	5–7
I	Kverneland «Vertical rhizome/root cutter» (Prototype)	The discs (diameter 36 cm) of the prototype make cuts for each 10 cm and fragment the horizontally growing rhizomes and roots with minimal soil disturbance.	8–12	–	5
I	Kverneland «Horizontal» rhizome/root cutter» (Prototype)	Flat shares like a goosefoot share 54 cm wide, cuts the vertical roots to an even depth throughout the whole width.	10–12		7

[a]stubble height.

from each replicate of four selected treatments (1, 3, 5, 7) each year in Experiment II, were analysed for disease infections by seed health methods at Kimen Seed Laboratory. Barley and oat grains were analysed for net blotch (*P. teres*) and leaf spot (*P. avenae*), respectively, by a *Pyrenophora* specific method where infected kernels develop pigment spots on moist blotters (ISTA 2018), and for seedling blight pathogens (*Fusarium* spp./*Microdochium* spp.) by a seedling symptom test (Jørgensen 1971). Wheat grains were analysed for glume blotch (*P. nodorum*) and seedling blight pathogens (*Fusarium* spp. and *Microdochium* spp.) by an agar plate method (ISTA 2018). One hundred kernels were analysed from each sample, i.e. 4×100 seeds from each experimental treatment.

Soil structure assessments (Exp. 1)

Undisturbed soil samples in cylinders were taken in autumn 2016 after harvest of the grain. From each plot, three undisturbed soil cores (100 cm^3) from the top layer (1–6 cm) were sampled and stored in a cool room. Water retention was measured at −20, −100, −1000 and −15000 hPa matric potential using sand boxes (Eijkelkamp) and ceramic plates (Richards 1947, 1948). The equivalent diameter of pores was obtained from the capillary rise relationship (Kutilek and Nielsen 1994). Air porosity at −100 hPa matric potential (pores > 30µm) was measured using an air pycnometer (Torstensson and Eriksson 1936), and total porosity was calculated as the sum of air porosity and volumetric water content at −100 hPa matric potential. Air permeability at −100 hPa matric potential was determined as described by Green and Fordham (1975). Visual judgment of soil structure was done according to Pearlkamp (1958).

Data analyses

General linear mixed models with normally distributed data were used in both experiments I and II to test the fixed effects of treatment, the combined effect of year and crop (here called year), nitrogen rate (only experiment II) and their mutual interactions. The dependent variables were dry matter of perennial weeds (total, *E. repens* and *S. arvensis* (only experiment I)), number of shoots of perennial weeds (total, *E. repens* and *S. arvensis* (only experiment I)) and in experiment I grain yields of spring barley (2014), spring oat (2015) and spring wheat (2016). The random effect was block within year in all analyses in experiment I. Since experiment II was a split-plot design, the random effects were block within year and the interaction between treatment and block within year. The repeated nature of the weed data with recordings made over time in the same plots was accounted for by including year as a repeated effect, with plot as the subject. An autoregressive correlation structure and variance was assumed between years. Weed biomass was not assessed in the initial years 2012 in experiment II and 2013 in experiment I, but the shoot counts made in the initial years showed no major differences among treatments irrespective of weed species, which means that the stands of perennial weeds were relatively uniform across the experimental area. For the analyses on weed biomass, the years 2013 (experiment II only), 2014, 2015 and 2016 (experiment I only) were included in the repeated statement, whereas for total shoot number the initial years 2012 (experiment II only) and 2013 (experiment I only) were included in addition to the other years.

The yield data in Experiment II was analysed by linear regression with increasing nitrogen input as the co-variate and year and treatment as categorical variables. The random effects were block within year and the interaction between treatment and block within year. The yield data in experiment I was also analysed by linear regression to study whether increasing total perennial weeds biomass affected grain yields. Weed biomass was the co-variate and year the categorical variable in this analysis, again with block within year as the random term.

The parameters of the linear models were estimated by residual likelihood estimations and calculations were made using the MIXED procedure of SAS (SAS release 9.2, SAS Institute Inc., Cary, N.C.). Means were calculated as least square means (LSM) and pair-wise comparisons between LSMs were based on *t*-tests, with probability values adjusted according to the Tukey method. The 5% level or less indicated a significant difference between means. The denominator degrees of freedom (DDF) in *F*-tests and *t*-tests for mean separations were calculated according to Kenward and Roger (1997). Data were either logarithmic or square root transformed whenever necessary to obtain homogeneity of variance. Assumptions for the statistical models used (independent experimental errors with homogeneity of variances, normally distributed and no outliers) were checked with visual inspection of standardised residuals plots; including normal probability plots and residuals versus fitted values of the response variables (y).

Results

Experiment I (different weed strategies)

Weeds

The ground coverage of the weeds differed considerably both between strategies and through the experimental years (Figure S1). The most frequent perennial weed species and total perennial weed biomass was included in the further statistical analyses.

Total perennial weed biomass and the principal species *E. repens* responded with significant main effects for treatment ($P = 0.0033$ (total) and $P = 0.0004$ (*E. repens*)) and year ($P = 0.0007$ (total) and $P = 0.0203$ (*E. repens*)). The two factors also interacted significantly for both variables: $P = 0.0156$ (total) and $P = 0.0065$ (*E. repens*). The biomass of *S. arvensis* was not affected by treatment and year.

The number of above-ground shoots of perennial weeds in total and of *E. repens* in particular was affected by treatment and year similarly as for biomass. Main effects of treatment and year were $P < 0.0001$ and $P = 0.0481$, respectively, for total shoot number and $P < 0.0001$ and $P = 0.1276$, respectively, for *E. repens*. Treatment and year interacted significantly with $P = 0.0285$ for total shoot number and $P = 0.0002$ for *E. repens*. For shoot number of *S. arvensis*, only the main effect of year was significant ($P = 0.0215$).

Tables 4 and 5 show the interactions between treatment and year for weed biomass and shoot numbers for perennials in total, *E. repens* and *S. arvensis*. In general, treatments 4 and 6 resulted in the smallest populations of perennial weeds in total 2015 and 2016, with effects mainly seen for *E. repens*. However, the populations were not significantly reduced when comparing 2016 with 2014, irrespective of the treatment. Comparisons between the initial shoot densities in 2013 and the final densities in 2016 only revealed one significant reduction, namely the 97% reduction of *E. repens* with treatment 6 ($P < 0.025$). The effect on *Sonchus arvensis* did not differ among treatments.

Fungal diseases

In general, only low levels of foliar diseases were seen in the fields. The few symptoms observed were evenly dispersed across treatments. In 2014, less than 1% of barley plants had net blotch symptoms at BBCH 20–30. Oat leaf spot incidence in 2015 was 3% at BBCH 20–30, and 8% at BBCH 65. No symptoms of wheat leaf spot diseases were observed in spring wheat (2016). Late in the season, at BBCH 70–80 (milk development/late milk), low levels of powdery mildew (*Blumeria graminea*) and rust diseases (*Puccinia* spp.) were observed evenly dispersed across treatments in all three years/all three cereal species. In harvested grain, the infection levels in barley (2014) and oats (2015) were 45% net blotch and 42% leaf spot, respectively, on average of the six treatments (strategies), with no significant differences between the strategies (Table 6). The infection levels of glume blotch in harvested spring wheat grain (2016) were low. However, grain harvested from plots that had been KvikUp-harrowed in autumn and spring, and sown with normal row spacing (strategy 6), had less infection than grain from plots with double row distance/hoeing (strategies 3 and 4), and the strategy with clover (strategy 2) (Table 6). Low levels of seedling blight were recorded in all three cereal species, with no differences between the different strategies.

Table 4. Least squares means (LSM_{transf}, square-root-transformed values with detransformed values in parentheses) of weed biomass (DM g m^{-2}) of perennials in total, *Elymus repens* and *Sonchus arvensis* shown for each treatment within the years 2014–2016 in experiment I. The relative change of the perennial weed population between years is shown for each treatment and weed category. All comparisons are based on Tukey tests.

Strategy	2014	2015		2016		
	LSM_{transf} (DM g m^{-2})	LSM_{transf} (DM g m^{-2})	% change 14 vs. 15	LSM_{transf} (DM g m^{-2})	% change 15 vs. 16	% change 14 vs. 16
Total biomass						
1	7.57 (57.3) a	9.60 (92.2) a	+61 ns	12.84 (165.0) a	+79 *	+188 **
2	6.64 (44.1) a	7.91 (62.6) a	+42 ns	10.09 (101.9) abc	+63 ns	+131 ns
3	6.98 (48.7) a	8.19 (67.1) ab	+38 ns	11.30 (127.7) ab	+90 (*)	+162 *
4	6.31 (39.8) a	3.97 (15.8) b	−60 ns	06.90 (47.60) bc	+201(*)	+20 ns
5	6.64 (44.1) a	8.16 (66.7) ab	+51 ns	09.43 (88.90) abc	+33 ns	+102 ns
6	4.68 (21.9) a	3.65 (13.3) b	−39 ns	05.63 (31.70) c	+138 ns	+45 ns
SED	*1.419*	*1.419*		*1.419*		
Elymus repens						
1	5.80 (33.6) a	7.95 (63.3) a	+88 ns	9.40 (88.3) a	+39 ns	+163(*)
2	3.23 (10.4) a	4.61 (21.2) ab	+104 ns	6.26 (39.1) ab	+84 ns	+276 ns
3	4.55 (20.7) a	5.44 (29.6) ab	+43 ns	7.46 (55.6) a	+88 ns	+169 ns
4	3.32 (11.0) a	1.64 (2.68) b	−76 ns	2.23 (4.98) b	+86 ns	−55 ns
5	4.07 (16.6) a	3.47 (12.0) ab	−28 ns	2.68 (7.21) ab	−40 ns	−57 ns
6	2.17 (4.71) a	0.75 (0.56) b	−88 ns	1.38 (1.90) b	+239 ns	−60 ns
SED	*1.369*	*1.369*		*1.369*		
Sonchus arvensis						
1	3.90 (15.2) a	3.66 (13.5) a	−11 ns	5.53 (30.6) a	+127 ns	+101 ns
2	5.23 (27.4) a	4.85 (23.5) a	−17 ns	6.29 (39.6) a	+69 ns	+45 ns
3	4.56 (20.8) a	3.88 (15.1) a	−27 ns	5.96 (35.5) a	+135 ns	+71 ns
4	4.71 (22.1) a	2.26 (5.09) a	−77 ns	4.42 (19.6) a	+285 ns	−11 ns
5	4.12 (17.0) a	5.19 (27.0) a	+59 ns	6.39 (40.8) a	+51 ns	+140 ns
6	3.62 (13.1) a	2.33 (5.43) a	−59 ns	4.36 (19.0) a	+250 ns	+45 ns
SED	*1.839*	*1.839*		*1.839*		

Different letters alongside LSM_{transf} in columns for each weed category and year indicate significant differences $P < 0.05$.
SED = maximum standard error of differences between LSM_{transf}.
ns = not significant.
(*) = $0.05 \le P < 0.1$.
* = $P < 0.05$.
** = $P < 0.01$.

Soil structure

In general, there were small effects on soil volumetric properties from the different strategies for control of perennial weeds (Table 7). However, KVIK-UP harrowing (strategy 5) in spring was among the treatments that resulted in lowest bulk density and highest pore volume. The greatest volume of pores >200 µm and pores > 30 µm were measured after normal sowing time, weed harrowing and mowing (treatment 1). The volume of 0,2 −30 µm pores (available water) was greatest for normal sowing time, weed harrowing and mowing + vertical cutter (strategy 2), and it seems that pore fraction 0,2 −3 µm (less available water) had increased compared with the other treatments. Air permeability showed the highest value (not significant) for treatment 1 (weed harrowing and mowing), followed by treatment 6 (KVIK-UP both in spring and autumn). The visual judgment of soil structure did not show any significant difference, but the KVIK-UP treatments were among the treatments with the highest score.

Crop yield

Crop yield analysis showed significant main effects of treatment ($P < 0.0001$), year ($P < 0.0001$) and a significant interaction between the two factors ($P = 0.0078$). The yield effects within years are shown in Table 8. Treatments 4 and 6 mostly gave the highest yield values in all three years, although not always significantly higher, but always significantly higher than untreated (treatment 1), except for treatment 4 in 2014. Yield differences between treatments within years could largely be explained by the reduction in perennial weed infestation, see Figure 1. This was particularly evident in 2015 and 2016, where perennial weed biomass was linearly correlated with crop yield.

Experiment II (inter-row hoeing and N-levels)

Weeds

The number of shoots of perennials in total was only affected by year (main effect, $P < 0.0001$), with shoot numbers (no. m^{-2}) averaging: 107.4 in 2012 (the initial population); 244.7 in 2013; 101.6 in 2014; and 16.9 in 2015. Inter-row cultivation at 24 cm row spacing only tended to lower shoot number (main effect, $P = 0.0878$) in comparison with no hoeing (12 cm row spacing), which was most pronounced for year 2015. A separate analysis of shoot number of the principal species, *E. repens*, showed that only year could explain the

Table 5. Least squares means (LSM_{transf}, square-root (total) and log-transformed (*E. repens* and *S arvensis*) values with detransformed values in parentheses) of number of perennial shoots in total, *Elytrigia repens* and *Sonchus arvensis*, respectively, shown for each treatment within the years 2013–2016 in experiment I. The relative change of the perennial weed population between years is shown for each treatment and weed category. All comparisons are based on Tukey-Kramer tests.

Strategy	2013	2014		2015		2016		
	LSM_{transf} (shoots m^{-2})	LSM_{transf} (shoots m^{-2})	% change 13 vs. 14	LSM_{transf} (shoots m^{-2})	% change 14 vs. 15	LSM_{transf} (shoots m^{-2})	% change 15 vs. 16	% change 13 vs. 16
Total number								
1	11.16 (124.6) a	11.71 (137.1) a	+10 ns	11.70 (137.0) a	−0.1 ns	16.57 (274.7) a	+99 ns	+120 ns
2	8.90 (79.3) a	9.08 (82.4) a	+4 ns	9.62 (92.6) ab	+12 ns	12.31 (151.6) ab	+64 ns	+48 ns
3	11.54 (133.2) a	10.77 (115.9) a	−13 ns	9.25 (85.6) ab	−26 ns	13.91 (193.6) ab	+126 ns	+45 ns
4	10.41 (108.4) a	7.65 (58.6) a	−46 ns	5.07 (25.7) b	−56 ns	08.88 (78.6) bc	+206 ns	−27 ns
5	9.32 (86.9) a	10.24 (104.9) a	+21 ns	9.05 (82.0) ab	−22 ns	11.77 (138.5) abc	+69 ns	+37 ns
6	9.62 (92.6) a	6.16 (37.9) a	−59 ns	5.08 (25.8) b	−32 ns	06.38 (40.7) c	+58 ns	−56 ns
SED	*1.524*	*1.524*		*1.524*		*1.524*		
Elymus repens								
1	3.12 (22.1) a	4.59 (97.7) a	+342 ns	4.57 (95.6) a	−2 ns	5.28 (195.4) a	+104 ns	+784 ns
2	2.87 (17.1) a	3.69 (39.4) a	+130 ns	3.28 (26.0) ab	−34 ns	4.30 (72.9) ab	+180 ns	+326 ns
3	2.96 (18.8) a	4.31 (74.2) a	+295 ns	3.83 (45.7) a	−38 ns	4.65 (104.4) a	+128 ns	+455 ns
4	2.97 (19.0) a	3.59 (35.6) a	+87 ns	1.41 (3.60) bc	−90 *	2.17 (8.2) bc	+128 ns	−57 ns
5	2.72 (14.7) a	4.09 (58.9) a	+301 ns	3.18 (23.5) ab	−60 ns	3.14 (22.6) ab	−4 ns	+54 ns
6	2.65 (13.6) a	2.24 (8.90) b	−35 ns	0.55 (1.23) c	−86 ns	−0.1 (0.4) c	−67 ns	−97 *
SED	*0.601*	*0.601*		*0.601*		*0.601*		
Sonchus arvensis								
1	1.07 (2.4) a	2.23 (8.8) a	+267 ns	1.68 (4.7) a	−47 ns	2.77 (15.5) a	+228 ns	+546 ns
2	1.45 (3.8) a	2.90 (17.6) a	+363 ns	2.96 (18.9) a	+7 ns	3.38 (28.9) a	+53 ns	+661 ns
3	2.06 (7.4) a	2.77 (15.4) a	+108 ns	2.45 (11.1) a	−28 ns	3.10 (21.8) a	+96 ns	+195 ns
4	2.20 (8.5) a	2.18 (8.3) a	−2 ns	1.97 (6.7) a	−19 ns	3.11 (22.0) a	+228 ns	+159 ns
5	1.49 (3.9) a	2.51 (11.8) a	+203 ns	2.79 (15.8) a	+34 ns	3.31 (26.7) a	+69 ns	+585 ns
6	1.85 (5.9) a	2.17 (8.3) a	+41 ns	2.18 (8.4) a	+1 ns	3.02 (20.0) a	+138 ns	+239 ns
SED	*0.938*	*0.938*		*0.938*		*0.938*		

Different letters alongside LSM_{transf} in columns for each weed category and year indicate significant differences $P < 0.05$. SED = maximum standard error of differences between LSM_{transf}. ns = not significant. * = $P < 0.05$.

variation significantly (main effect: $P = 0.0009$), again with 2015 having the smallest population: 13.0 shoots m^{-2}.

The biomass of perennials in total responded to year (main effect, $P < 0.0001$), treatment (main effect, $P = 0.0390$) and the interaction between the two factors ($P = 0.0129$). The effects were mainly driven by *E. repens* and partly by *Vicia cracca* (tufted vetch). Similar to shoot numbers, nitrogen level did not explain any of the biomass variation except for *V. cracca,* which showed biomass reduction with increasing N-levels (main effect, $P = 0.0163$). Figure 2 illustrates the total perennial biomass plotted against increasing N-levels and in relation to year and treatment. Hoeing at 24 cm row spacing resulted in significantly less perennial biomass than when hoeing at 12 cm spacing, primarily in 2015. While 2015 had the lowest shoot number of perennials in total of all years, 2015 also had the greatest amount of perennial weed biomass. The shoot numbers in the other years originated primarily from many tiny shoots of *Stachys palustris* (marsh woundwort), especially in 2013 and *V. cracca*. Shoot growth of *E. repens* was also less vigorous in 2013 and 2014 (data not shown).

Fungal diseases

As in Experiment I, only low levels of foliar diseases were observed in all three years throughout the experimental fields (across treatments) in Experiment II. Barley net blotch occurred on 3% of the plants in 2013 and on less than 1% in 2014, at BBCH 20–30. In 2015 (oats), 3% of the plants had leaf spot symptoms at BBCH 20–30 and 8% at BBCH 65. Also in this experiment, low levels of powdery mildew and rust diseases were observed in

Table 6. Diseases (% infected kernels) recorded by laboratory analyses of grain harvested from experiment I in 2014, 2015 and 2016.

			2014 (barley)		2015 (oat)		2016 (spring wheat)		
							Seedling blight		
Strategy	Row distance	N (kg ha^{-1})	Net blotch	Seedling blight	Leaf spot	Seedling blight	Fusarium spp.	Microdochium spp.	Glume blotch
1	12	100	47	4	41	4	6	3	2 ab
2	12	100[a]	39	3	46	4	3	1	6 a
3	24	100	50	7	43	8	5	4	6 a
4	24	100	43	6	40	4	1	3	7 a
5	12	100	49	4	39	4	3	3	3 ab
6	12	100	44	4	43	4	3	2	1 b
P-value:			0.14	0.38	0.87	0.14	0.43	0.52	0.03

[a] undersown white clover. 2014: 50 Kg N.

Table 7. Soil volumetric properties, air permeability and visual judgment of soil structure for the different strategies for control of perennial weeds (Experiment 1).

Strategy	Bulk density g cm^{-3}	Pore volume Vol%	Pore volume (µm) > 200	> 30	0,2–30	0,2–3	Air perme-ability µm^2	Visual judgment of soil structure
1	1.35	48.1	7.6	10.7	21.0	17.4	9.7	5.6
2	1.36	47.8	4.1	7.0	23.9	20.4	2.7	5.4
3	1.39	46.2	6.0	8.3	21.1	17.7	4.1	5.4
4	1.35	48.2	5.7	8.7	22.8	18.9	3.8	6.9
5	1.39	46.7	4.9	8.0	22.0	18.2	3.4	7.3
6	1.34	48.8	7.1	10.2	22.6	18.7	7.5	6.5
Sign.	ns	ns	*	ns	*	*	ns	ns

ns = not significant.
* = $P < 0.05$.

all three years late in the growing season (at BBCH 70–80, milk development/late milk). In harvested grain, the infection levels of net blotch in barley in 2013 and 2014, and of leaf spot in oats in 2015 were 19%, 43% and 37% infected kernels, respectively, on average of the four tested treatments. There was a trend (not statistically significant) towards lower fungal infections in grain from the lowest N level (50 kg N) than from the higher level (150 kg N) in all three years (Table 9). The levels of pathogens causing seedling blight in the harvested grain was low also in this experiment (as in Experiment I).

Crop yield

Grain yields increased linearly with increasing nitrogen input and could be described by one common slope ($P < 0.0001$), irrespective of the two categorical variables year and treatment. Year had a strong main effect ($P < 0.0001$) but interacted with treatment ($P = 0.0390$). The simplest model, in which all non-significant effects were excluded, is shown in Table 10 and Figure 3. Treatment only affected yields in oats in 2015, when yields were 17% higher for 24 cm row spacing + hoeing as compared to 12 cm spacing. All three highest N-levels gave higher yield than 50 kg N, and 200 kg N gave higher yield than 100 kg N for both 2013 and 2014. In 2015, the two highest levels, 150 kg N and 200 kg N, gave higher yield than the two lowest N-levels, with no difference between the two highest N-levels. Crop yields increased while perennial weed biomass remained the same with increasing nitrogen supply, which implies that the crops utilised the added resources better than the weeds.

Perennial weed biomass was not included in the analyses as a co-variate in addition to nitrogen input because these data were strongly confounded with year and treatment. In addition, the range of weed biomass within year and treatment was too small to cause any significant correlations between yields and weed biomass.

Table 8. Least squares means (LSM) of grain yield (kg ha^{-1}) of spring barley (2014), spring oat (2015) and spring wheat (2016) in experiment I. All comparisons are based on Tukey tests.

Strategy	Barley (2014)	Oat (2015)	Wheat (2016)
1	2923.9 ab	3702.4 a	1468.0 a
2	2628.5 a	3815.5 ab	1628.3 ab
3	2958.4 ab	4505.5 b	2573.3 c
4	3157.8 ab	4718.5 b	2816.2 c
5	3556.4 bc	3962.5 ab	2344.6 bc
6	4008.5 c	4542.7 b	3014.7 c
SED	*206.07*	*250.97*	*268.97*

Different letters alongside LSMs in columns for each year indicate significant differences $P < 0.05$.
SED = maximum standard error of differences between LSMs.

Discussion

Strategy 1, without stubble cultivation or hoeing treatments, was considered as the standard treatment of Experiment I (Table 2). According to studies of Salonen

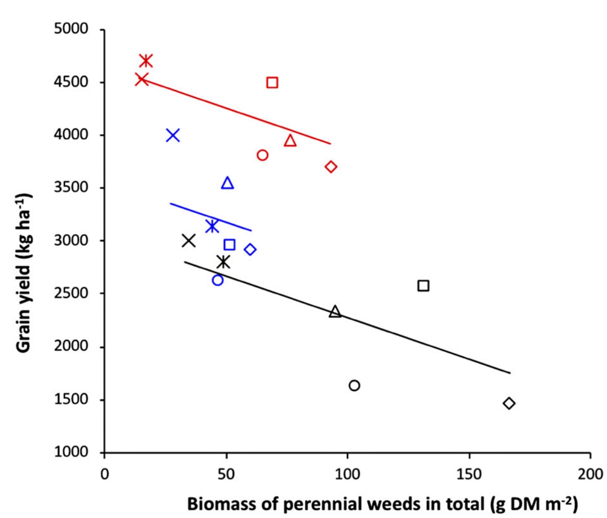

Figure 1. The relationships between biomass of perennial weeds in total (g DM m^{-2}) and grain yield (kg ha^{-1}) of spring barley in 2014 (blue colour), spring oat in 2015 (red) and spring wheat in 2016 (black) in experiment I. The relationships can be described by one common slope −7.82 (kg ha^{-1} g^{-1} m^2) and three intercepts: 2014 = 3569.3 (kg ha^{-1}), 2015 = 4643.2 (kg ha^{-1}), 2016 = 3060.0 (kg ha^{-1}). Non-transformed weed biomass values was used in the regression. ◇ = 1, ○ = 2, □ = 3, ✱ = 4, Δ = 5 and ✕ = 6.

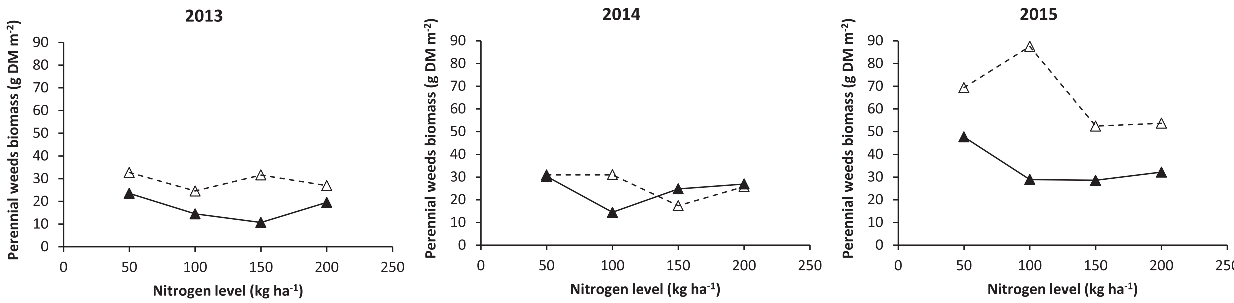

Figure 2. Least square means (LSM) (shown as back-transformed LSMs from log-transformation) of weed biomass (g DM m^{-2}) of all perennial weed species in total in experiment II. LSMs are plotted against increasing nitrogen input and shown for the categorical variables year and treatment. ▲ = 24 cm inter-row spacing + hoeing, Δ = 12 cm inter-row spacing without hoeing.

Table 9. Diseases (% infected kernels) recorded by laboratory analyses of grain harvested from experiment II in 2013, 2014 and 2015.

		2013 (barley)		2014 (barley)		2015 (oat)	
Row distance	N (kg/ha)	Net blotch	Seedling blight	Net blotch	Seedling blight	Leaf spot	Seedling blight
12	50	19	3	37	1	26	4
12	150	26	3	43	1	40	5
24	50	14	2	38	3	35	5
24	150	18	3	52	3	47	5
P-value:		0.07	0.76	0.29	0.47	0.12	0.91

et al. (2001) and Sundheim et al. (2014), this treatment is very close to the practice of many organic farmers today and the authors conclude needs for improvements for controlling weeds. The strategies consisting of one direct weed control measure, i.e. hoeing (strategy 3), 'KVIK-UP' harrowing in spring (strategy 5) and the use of the 'Vertical-cutter' in autumn (strategy 2) did not result in decreased biomass or shoot number for either total records or specific weed species. These treatments did not suppress any of the specific weed species in our study (Tables 4 and 5). Nevertheless, it is interesting to observe that the composition of weed species changed during the years in strategy 5, with a decrease of *E. repens* and an increase of *S. arvensis*, although these results were not significant (Figure S1, Tables 4 and 5). New studies are needed to verify whether a short period of 'KVIK-UP' bare fallow in spring could be sufficient for control of *E. repens* in fields dominated by this species, as well as verifying the risk of promoting *S. arvensis*. The 'vertical cutter' fragments shallow-growing rhizomes and creeping roots with minimal disturbance. This may have several environmental benefits, but lack of weed control of this strategy post-harvest (in autumn) was recently shown by Bergkvist et al. (2017). However, Ringselle et al. (2018), using the same vertical cutter for control of *E. repens* when renewing a ley, concluded that rhizome fragmentation by this tool reduced growth of *E. repens* and benefited ryegrass and white clover crops.

Table 10. Parameter estimates for grain yields of spring barley (2013 and 2014) and spring oat (2015) regressed linearly against increasing nitrogen level in experiment II. Parameter estimates are from the simplest model. Standard errors of the estimates are shown in parentheses.

Year (crop)	Treatment	Intercept (kg ha^{-1})	Slope (kg ha^{-1} kgN^{-1} ha)
2013 (Spring barley)	12 cm	2885.2 (147.8)	11.63 (0.827)
	24 cm + hoeing	2885.2 (147.8)	11.63 (0.827)
2014 (Spring barley)	12 cm	1967.2 (145.1)	11.63 (0.827)
	24 cm + hoeing	1967.2 (145.1)	11.63 (0.827)
2015 (Spring oat)	12 cm	3273.0 (172.6)	11.63 (0.827)
	24 cm + hoeing	3836.9 (177.4)	11.63 (0.827)

Two direct weed control measures within an annual cycle, stubble harrowing in autumn and spring (strategy 6) *or* stubble cultivation in autumn and hoeing (strategy 4) was necessary for controlling the whole perennial weed flora (Figure S1, Tables 4 and 5). Although not always resulting in significantly lower numbers of weeds, these two treatments clearly distinguished themselves from all the other treatments. The combination of 'KVIK-UP' harrowing and hoeing, two potential spring – early summer measures, was not included in our study. However, it would have been interesting to have included this treatment because it might minimise the risk of soil erosion and nutrient leaching linked to intensive soil cultivation in autumn.

Soil structure was evaluated by measuring various volumetric properties of the soil (Table 7). These

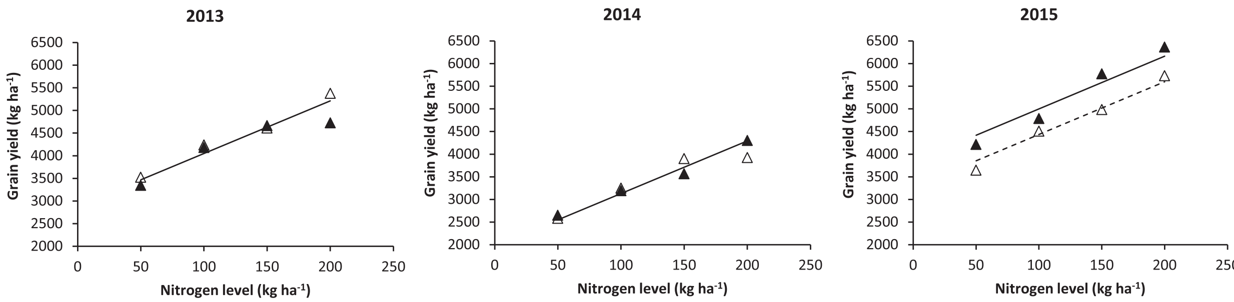

Figure 3. Linear regression of grain yield against increasing nitrogen input shown for the categorical variables year and treatment in experiment II. Curves were fitted according to the parameter estimates shown for the simplest model in Table 10. ▲ = 24 cm inter-row spacing + hoeing, Δ = 12 cm inter-row spacing without hoeing.

measurements show only few significant effects of the strategies. Even if the various parameters do not show the same trend, it can be generalised that more intensive treatments such as KVIK-UP did not harmed the soil structure in our experiment. Our measurements were made after harvest but before any autumn treatments, and we expect insignificant direct effects from autumn treatments because the soil is ploughed in spring. That can also be true for the spring treatment with KVIK-UP, since the soil is ploughed within short time after the use of the KVIK-UP. Treatment 2, with the use of a vertical cutter, seems to have changed the pore size distribution towards more pores in the fraction 0,2–3 µm probably because of the disk which are cutting the soil, also compact the soil. Air permeability also shows this trend, although it is not significant. However, the effect measured on the soil structure will not have any influence on plant growth. The workability of the soil may have been affected by the autumn treatment. The disk harrowed and KVIK-UP harrowed plots may have been drier at the time of normal sowing than plots that was mowed because of different evaporation from the surface. For strategies 5 and 6 with use of KVIK-UP in spring to the same time as normal sowing time, but so ploughed about 1 weeks later could also have been ploughed and sown with another soil moisture content as compared to treatments with normal sowing time.

Because the combination of best weed control in strategies 4 and 6 and no measured harmful effects on soil structure, it is not surprising that the highest yields were achieved in strategy 4 and 6. The weed data, however, cannot alone explain all yield responses. For example in 2016 strategy 3 resulted in grain yields similarly to the most effective weed control strategies 4 and 6, though strategy 3 had very large biomass, which was significantly higher than those measured for strategies. The different weed management strategies did not influence on levels of net blotch and leaf spot in harvested grains of barley and oat, respectively. In spite of modest development of disease symptoms in the fields, considerable infections of net blotch and leaf spot pathogens were detected in harvested barley and oat grains, respectively (Table 6). This was probably caused by the relatively wet conditions promoting disease spread in the last part of the growing season.

Hoeing and 24 cm spacing resulted in significantly less perennial biomass as compared to 12 cm spacing. The differences were greatest in 2015, followed by 2013 and 2014 (Figure 2). Differences between years were probably most related to different number of hoeing operations between years (2015 = 3 times; 2013 = 2 times; 2014 = 1 time). As an average over years, each hoeing operation corresponded to a biomass decrease of ≈ 15 percent per hoeing (data not shown), slightly higher than the ca. 10 percent per hoeing (2 yr. average) against *C. arvense* reported by Graglia et al. (2006). Melander et al. (2005) previously summarised that widening crop row spacing to allow for inter-row hoeing may reduce yields under conventional growing conditions, but concluded also that evidence on the effect of row-spacing on yield is inconclusive in both spring and winter cereals. Moreover, recent results obtained from three-year experiments with organically grown spring barley and spring wheat did not reveal any unambiguous yield penalty associated with widening inter-row spacing from 125 mm to 150, 200, 250 or even 300 mm (Melander et al. 2018). This can be exemplified by Andersson (1983), who showed that when row spacing of winter wheat was increased from 100 to 220 mm with the same seeding rate, the largest yield was achieved with 100-mm row spacing, and yield was decreased by 0.7% for every centimetre increase of row distance. In contrast to this, neither Rasmussen (1998) nor Tillett et al. (1999) found any yield reduction when increasing row spacing of winter wheat from 100–120 to 200–220 mm. In clear contrast to our results, Lötjönen and Mikkola (2000) in Finland found that a similar spacing increase (125–250 mm) in spring barley caused yields to decrease by 12–13%, and interrow hoeing did not increase the yield further. One explaining factor of these contradictory results may be differences in weed flora and weed pressure, which gave higher advances of hoeing in our study (Figure 3).

Increased nitrogen level did not explain any of the variation of weed biomasses except for *V. cracca* where biomass was reduced by increasing N-level (data not shown). *E. repens* is exemplified by Håkansson (2003) as a species that responds positively to stronger fertilisation, but this was not shown in our study. However, other studies have demonstrated contradictory results with *E. repens* and its response to organic amendments when competing with arable crops (Rasmussen et al. 2014; Melander et al. 2016). Another species, *S. arvensis* is exemplified as a species that responds opposite, i.e. stronger fertilisation decreases the competition ability of this species (Håkansson 2003; Eckersten et al. 2010).

Also in Experiment II (12 vs. 24 cm row distance and different N levels), considerable infections of net blotch and leaf spot pathogens were detected in harvested barley and oat grains, respectively, in spite of low levels of symptoms in the fields (Table 9). However, double spacing and hoeing did not increase fungal disease levels in harvested grain compared to normal spacing. On the contrary, there was a tendency of less net blotch in barley from double vs normal row distance in 2013. In the spring wheat experiment in 2016 (weed control strategies) the level of glume blotch in harvested grain was low, but tended to be higher in the treatments with wide compared to normal row spacing (24 vs. 12 cm). It is unlikely that this had any practical influence. However, it can be mentioned that Broscious et al. (1985) reported more glume blotch at wider row spacing (18 vs. 13 cm) in two experiments, although in most cases row spacing did not consistently affect the disease severity. In a study by Orth and Grybauskas (1994), wide rows (20 vs. 10 cm) tended to increase glume blotch severity, although grain infection was not affected or decreased with wide row spacing. A more recent study (Salgado et al. 2017) did not observe high enough leaf blotch intensity to evaluate the row-spacing effect. Tompkins et al. (1993) reported that narrow row spacing (9 vs. 36 cm) produced a canopy microclimate favourable for the development of glume blotch. These somewhat inconsistent observations indicate a need for further field studies on the effects of row distance on fungal diseases in cereals, preferably at a number of locations and soil types, and in more years to have different weather conditions. No literature was found concerning fungal disease development and row distances in barley and oats.

The influence of N supply on cereal diseases is reported to be contradictory (Walters and Bingham 2007). Increased N rates have been shown in a number of studies to increase fusarium head blight, wheat leaf spot complex, barley net blotch, powdery mildew, rust diseases, etc (e.g. Lemmens et al. 2004; Baeckström et al. 2006; Askegaard et al. 2011; Salgado et al. 2017). In our study, we did not see a significant effect of nitrogen fertilisation on fungal disease levels, although there was a trend towards increased disease with increased N supply. Other studies have also reported no effect of N on the severity of cereal diseases, e.g. Salgado et al. (2017), who did not find a significant effect of N on FHB or the mycotoxin deoxynivalenol (DON).

The use of undersown white clover did not reduce the disease incidences in our experiment (Table 6). This deviates from a number of studies that have reported reduced fungal disease severity with the use of green manures and living mulches; e.g. Costanzo and Barberi (2016) reported that the presence of legume living mulch reduced the severity of the wheat leaf spot complex by 37% in average, and Kosinski et al. (2011) found that kura clover living mulch significantly reduced the development of barley leaf diseases. In a previous Norwegian study, the frequencies of net blotch infected barley seedlings were significantly reduced after soil amendments of grass and clover in a greenhouse experiment using two heavily infected seed lots (Brodal et al. 2008).

As commented by a number of studies, cereal diseases are greatly influenced by weather conditions in the growing season (e.g. Baeckström et al. 2006; Walters and Bingham 2007). In our experiments, it is likely that weather conditions late in the growing season caused considerable development of barley net blotch and oat leaf spot infections evenly dispersed throughout the experimental fields.

We can conclude that in Experiment I the strategies consisting of no or one direct weed control measure clearly did not control the perennial weed flora (Figure S1, Tables 4 and 5). The two seasonal control measures gave a similar and satisfactory weed control as well as the highest crop yield. Since the combination of best weed control in the two strategies and no measured harmful effects on soil structure or increase of diseases in these strategies, it is not surprising that the highest yields also were achieved here. The different strategies for control of perennial weeds did not affect the soil structure, as evaluated by pore size distribution, air permeability and visual judgment. In Experiment 2, hoeing and 24 cm spacing resulted in significantly less perennial biomass as compared to 12 cm spacing. As an average over years, each hoeing operation corresponded to a biomass decrease of ≈ 15 percent per hoeing. Double row spacing and hoeing did not increase disease levels in harvested grain compared to normal spacing. Increased nitrogen level did not explain any of the variation of weed biomasses, except for *V. cracca* where biomass was reduced by increasing N-level. In our study, we did not see a significant effect of nitrogen fertilisation on the fungal disease levels, although there seemed to be a trend towards increased disease with increased N supply. In the two first experimental years, the crop yield was similar for the two spacing levels, the third year hoeing and 24 cm gave the highest yield. The study shows that both inter-row hoeing and the use of weed harrows, especially those that both desiccate and starve the perennial weeds, are important puzzle pieces in when developing integrated pest management practice and organic farming. Our results also show that relatively intensive soil cultivation may not be harmful for the soil structure when carried out when the soil is workable.

Acknowledgements

We thank the 'NMBU-SKP-Center for field experiments', especially Jens Andreas Randem and Svend Pung, but also Samuel Habte and Arkan Rezak Alazawy, both NIBIO, for their technical assistance. Furthermore, we would like to thank the staff at Kimen Seed Laboratory for analysing harvested grain samples. The study received financial support from the Research Council of Norway through the project (no. 207686) 'Sustained and increased organic cereal production by improved nutrient supply and pest control' (short name 'Økokorn 2012–2016') as well as from the companies 'Myhres Maskinomsetning', 'Global-Enviro', 'Lindum Bioplan', 'Norgesfôr Vestfold', 'Hadeland og Ringerike avfallsselskap AS' and 'GLØR IKS'.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by The Research Council of Norway project (no. 207686).

Notes on contributors

Lars Olav Brandsæter has been Associate Professor (2007–2016) and Professor (2017–…) in weed science at the Norwegian University of Life Sciences science since 2007. He has a second position as a senior scientist at the Norwegian Institute of Bioeconomy Research. He received his PhD in 1997 at the Norwegian University of Life Sciences. His main areas of research are weed biology and ecology, and non-chemical weed control with special emphasis on perennial weed species in grassland and cereals as well as control of alien weeds.

Kjell Mangerud was in the past associate professor at Inland Norway University of Applied Sciences. After retiring from his main position he has a second position as a scientist at the Norwegian Institute of Bioeconomy Research. His main areas of research are soil tillage and weed management.

Lars Andersson received his PhD in 1995, and since then he has continued to teach and conduct research at SLU (Sweden). In 1999, he became Associate Professor (docent) and in 2010 Professor. Since 2012 he have been working as Senior Lecturer/ Extension Specialist in Crop Production Science with a focus on weeds. In 2015 he became programme director of the transdisciplinary research platform Future Agriculture. His research area and area of expertise primarily concerns weed biology, and the possibility to use biological knowledge to develop resource effective and sustainable control strategies.

Trond Børresen has been professor in soil management at the Norwegian University of Life Sciences science since 1994. He received his PhD in 1987 at the Norwegian University of Life Sciences. His areas of research are soil physics, soil structure, soil compaction, soil tillage, soil erosion and soil quality under different management systems.

Guro Brodal is a Senior Researcher in plant pathology at Norwegian Institute of Bioeconomy Research (NIBIO), Division of Biotechnology and Plant Health. Her research includes epidemiology and integrated management of fungal diseases on agricultural crops (small grain cereals, oil seed crops, legumes, grasses) including seed-borne diseases. Recent years her main focus has been on Fusarium and mycotoxins in oats and wheat, including agronomic strategies to reduce mycotoxin risk. She also works on seed-borne diseases in cereals for organic farming and pathogens on conifer seeds.

Bo Melander is a weed scientist with > 30 years of experience working with weed management in organic and conventional cropping systems. He chaired the European working group on Physical and Cultural Weed Control for twelve years.

References

Andersson B. 1983. Odlingstekniska försök med höstvete: verkan av såtid, utsädesmängd, radavstånd, kvävegödsling och skördetid i kombination med olika sorter. (Studies on cultivation technique of winter wheat: influence of sowing time, seed rate, row space, nitrogen fertilization and harvest time combined with different cultivars. (With English summary). Uppsala, Sweden: Institutionen forväxtodling. Rapport 1, Swedish University of Agricultural Sciences. pp. 1–63.

Askegaard M, Thomsen IK, Berntsen J, Hovmøller SS, Kristensen K. 2011. Performance of spring barley varieties and variety mixtures as affected by manure application and their order in an organic crop rotation. Acta Agric. Scand Sect B Soil Plant Sci. 61:421–430.

Baeckström G-L, Lundegård B, Hanell U. 2006. The interactions between nitrogen dose, year and stage of ripeness on nitrogen and trace element concentrations and seed-borne pathogens in organic and conventional wheat. J Sci Food Agric. 86:2560–2578.

Bakken AK, Breland TA, Haraldsen TK, Aamlid TS, Sveistrup T. 2006. Soil fertility in three cropping systems after conversion from conventional to organic farming. Acta Agric Scand Sect B Soil Plant Sci. 56:81–90.

Bergkvist G, Ringselle B, Magnuski E, Mangerud K, Brandsæter LO. 2017. Control of *Elymus repens* by rhizome fragmentation and repeated mowing in a newly established white clover sward. Weed Res. 57:172–181.

Brandsæter LO, Goul Thomsen M, Wærnhus K, Fykse H. 2012. Effects of repeated clover undersowing in spring cereals and stubble treatments in autumn on *Elymus repens, Sonchus arvensis* and *Cirsium arvense*. Crop Prot. 32:104–110.

Brandsæter LO, Mangerud K, Helgheim M, Berge TW. 2017. Control of perennial weeds in spring cereals through stubble cultivation and mouldboard ploughing during autumn or spring. Crop Prot. 98:16–23.

Brodal G, Drægni K, Skjelvåg AO, Henriksen B. 2008. Transmission of *Drechlera teres* from seed to seedlings in relation to soil organic content. J. Pl. Path. 90(2, Supplement):S2.151.

Broscious SC, Frank JA, Frederick JR. 1985. Influence of winter wheat management practices on the severity of powdery mildew and septoria blotch in Pennsylvania. Phytopath. 75:538–542.

Burdon JJ, Chilvers GA. 1982. Host density as a factor in plant disease ecology. Ann Rev Phytopath. 20:143–166.

Cormack WF. 1999. Testing a stockless arable organic rotation on a fertile soil. In: Olesen JE, Eltun R, Gooding MJ, Steen Jensen E, Köpke U, editors. Designing and testing crop rotation for organic farming. Proceedings from an international workshop. DARCOF Report No. 1 (1999). p. 350.

Costanzo A, Barberi P. 2016. Field scale functional agrobiodiversity in organic wheat: effects on weed reduction, disease susceptibility and yield. Eur J Agron. 76:1–16.

Dock-Gustavsson A-M. 1997. Growth and regenerative capacity of plants of Cirsium arvense. Weed Res. 37:229–236.

Eckersten H, Lundkvist A, Torsell B. 2010. Comparison of monocultures of perennial sow-thistle and spring barley in estimated shoot radiation-use and nitrogen-uptake efficiencies. Acta Agric Scand Sect B Soil Plant Sci. 60:126–135.

Fahnbulleh CGV. 2014. The effects on soil physical properties of long term soil tillage and soil compaction. Master thesis. Department of Environmental Sciences, Norwegian University of Life Sciences: p. 57.

Frøseth RB, Bakken AK, Bleken MA, Riley R, Pommeresche R, Thorup-Kristensen K, Hansen S. 2014. Effects of green manure herbage management and its digestate from biogas production on barley yield, N recovery, soil structure and earthworm populations. Eur J Agron. 52:90–102.

Graglia E, Melander B, Jensen RK. 2006. Mechanical and cultural strategies to control Cirsium arvense in organic arable cropping systems. Weed Res. 46:304–312.

Green RD, Fordham SJ. 1975. A field method for determining air permeability in soil. Soil Physical Conditions and Crop Production. Tech. Bull. No. 29, Ministry of Agriculture, Fisheries and Food. HMSO, London, p. 273–287.

Håkansson S. 2003. Weeds and weed management on arable land: an ecological approach. Wallingford, Oxon, UK: CABI Publishing. 274 pp.

ISTA. 2018. International Rules for Seed Testing. Chapter 7: Validated Seed Health Testing Methods. The International Seed Testing Association (ISTA), Zürichstr. 50, CH-8303 Bassersdorf, Switzerland. [accessed 2018 March 18]. https://www.seedtest.org/en/seed-health-methods-_content—1–1452.html.

Jørgensen J. 1971. The Doyer filter paper method in health testing of barley seed. Proc Int Seed Test Assoc. 36:325–333.

Kenward MG, Roger JH. 1997. Small sample inference for fixed effects from restricted maximum likelihood. Biometrics. 53:983–997.

Korsaeth A, Eltun R. 2008. Synthesis of the Apelsvoll cropping system experiment in Norway – nutrient balances, use efficiences and leaching. In: Kirchmann H., Bergström L., editor. Organic crop production – ambitions and limitations. UK: Springer Science + Business Media B.V.; p. 117–141.

Kosinski SM, King JR, Harker KN, Turkington TK, Spaner D. 2011. Barley and triticale underseeded with a kura clover living mulch: effects on weed pressure, disease incidence, silage yield, and forage quality. Can J Plant Sci. 91:667–687.

Kutilek M, Nielsen DR. 1994. Soil Hydrology. Cremlingen-Destedt (Germany): Catena Verlag.

Lemmens M, Haim K, Lew H, Ruckenbauer P. 2004. The effect of nitrogen fertilization on *Fusarium* head blight development and deoxynivalenol Contamination in wheat. J Phytopath. 152:1–8.

Lötjönen T, Mikkola H. 2000. Three mechanical weed control techniques in spring cereals. Agric Food Sci Finl. 9:269–278.

Marti M. 1984. Kontinuierlicher Getreidebau ohne Pflug im Südosten Norwegens - Wirkung auf Ertrag, Physikalsche und Chemische Bodenparameter. Dr. scient. thesis, Agricultural University of Norway, p. 155.

Melander B, Holst N, Rasmussen IA, Hansen PK. 2012. Direct control of perennial weeds between crops – implications for organic farming. Crop Prot. 40:36–42.

Melander B, Jabran K, De Notaris C, Znova L, Green O, Olesen JE. 2018. Inter-row hoeing for weed control in organic spring cereals – influence of inter-row spacing and nitrogen rate. Europ J Agron. 101:49–56.

Melander B, Rasmussen IA, Olesen JE. 2016. Incompatibility between fertility building measures and the management of perennial weeds in organic cropping systems. Agric Ecosyst Environ. 220:184–192.

Melander B, Rasmussen IA, Bárberi P. 2005. Symposium integrating physical and cultural methods of weed control -examples from European research. Weed Sci. 53:369–381.

Myrbeck Å, Stenberg M, Arvidsson J, Rydberg T. 2012. Effects of autumn tillage of clay soil on mineral N content, spring cereal yield and soil structure over time. Eur J Agron. 37:96–104.

Njøs A, Børresen T. 1991. Long-term experiment with straw management, stubble cultivation, autumn and spring ploughing on a clay soil in S.E. Norway. Soil Till Res. 21:53–66.

Orth CE, Grybauskas AP. 1994. Development of septoria nodorum blotch on winter wheat under two cultivation schemes in Maryland. Plant Dis. 78:736–741.

Pearlkamp PK. 1958. A visual method of soil structure evaluation. Int Symp on Soil Structure, Gent. 24:28–31.

Permin O. 1961. Jordbearbejdningens betydning for bekæmpelse af rodukrudt. Tidsskrift for Planteavl. 64:875–888.

Rasmussen J. 1998. Ukrudtsharvning i vinterhvede. (Weed harrowing in winter wheat. With English summary). In Proceedings 15th Danish Plant Protection Conference /Weeds. Nyborg, Denmark: Danish Institute of Agricultural Sciences, p. 179–189.

Rasmussen IA, Melander B, Askegaard M, Kristensen K, Olesen JE. 2014. *Elytrigia repens* population dynamics under different management schemes in organic cropping systems on coarse sand. Eur J Agron. 58:18–27.

Richards LA. 1947. Pressure-membrane apparatus, construction and use. Agric Eng. 28:451–454. 460.

Richards LA. 1948. Porous plate apparatus for measuring moisture retention and transmission by soils. Soil Sci. 66:105–110.
Ringselle B, Bertholtz E, Magnuski E, Brandsæter LO, Mangerud K, Bergkvist G. 2018. Rhizome fragmentation by vertical disks reduces *Elymus repens* growth and benefits Italian ryegrass-white clover crops. Front. Plant Sci. [11 January 2018]. doi:10.3389/fpls.2017.02243.
Salgado JD, Lindsey LE, Paul PA. 2017. Effects of row spacing and nitrogen rate on wheat grain yield and profitability as influenced by diseases. Plant Dis. 101:1998–2011.
Salonen J, Hyvonen T, Jalli H. 2001. Weeds in spring cereal fields in Finland - a third survey. Agr Food Sci. 10:347–364.
Sundheim L, Brandsæter LO, Brodal G, Eriksen GS, Hofsvang T, Magnusson C, Remberg SF, Uhlen AK. 2014. Comparison of organic and conventional food production. Part I: Plant health and plant production. Opinion of the Panel on Plant Health of the Norwegian Scientific Committee for Food Safety. Oslo, Norway. VKM Report 2014, 22–1. 127pp + appendix 185 pp.
Thomsen MG, Mangerud K, Riley H, Brandsæter LO. 2015. Method, timing and duration of bare fallow for the control of *Cirsium arvense* and other creeping perennials. Crop Prot. 77:31–37.
Tillett ND, Hague T, Blair AM, Jones PA, Ingle R, Orson JH. 1999. Precision inter-row weeding in winter wheat. In Proceedings 1999 Brighton Crop Protection Conference - Weeds: Brighton, U.K., British Crop Protection Council, p. 975–980.
Tompkins DK, Fowler DB, Wright AT. 1993. Influence of agronomic practices on canopy microclimate and septoria development in no-till winter wheat produced in the Parkland region of Saskatchewan. Can J Plant Sci. 73:331–344.
Torstensson G, Eriksson S. 1936. A new method for determining the porosity of the soil. Soil Sci. 42:405–414.
Van Bruggen AHC, Finckh MR. 2016. Plant disease and management approaches in organic farming systems. Ann Rev Phytopath. 54:25–54.
Vanhala P, Lotjonen T, Hurme T, Salonen J. 2006. Managing Sonchus arvensis using mechanical and cultural methods. Agric Food Sci. 15:444–458.
World Reference Base. 2006. A framework for international classification, correlation and communication. Food and Agriculture Organization of the United Nations, Rome, World Soil Resources Reports 103, 145 pp.
Walters DR, Bingham IJ. 2007. Influence of nutrition on disease development caused by fungal pathogens: implications for plant disease control. Ann Appl Biol. 151:307–324.