Highlights

- traditional weed control strategies tend to impact negatively the environment
- cover crop cultivation prior to a maize crop can be efficient to control weeds
- niger, sunflower, pea and phacelia were the most successful species in this respect
- some cover crops also improved maize yield compared to the control
- this study shows that cover crops are efficient to reduce weed control intensity

Title

Cover crops to secure weed control strategies in a maize crop with reduced tillage

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Declarations of interest: none

Abstract

To better understand the ability of cover crops to control weeds in a maize crop (*Zea mays*, L.) grown with reduced tillage, four field experiments were set up from 2009 to 2014 in the western part of Switzerland. Ten non-wintering cover crop species were compared to a no cover crop control in strip plot experiments including different weeding strategies. The weeding strategies included no or minimum tillage before maize seeding. Soil coverage by weeds at early maize stage (2-4 leaf stage) varied drastically between weeding strategies and years. In most cases, cover crops allowed to reduce the weed pressure compared to the no cover crop control. The most efficient cover crop species varied from year to year, but niger (*Guizotia abyssinica*, (L.f.) Cass.), sunflower (*Helianthus annuus*, L.), field pea (*Pisum sativum*, L.) and phacelia (*Phacelia tanacetifolia*, Benth.) gave the best overall results. Maize yield differed significantly between weeding strategies only one year, with higher yield observed with minimum tillage. In some situation, cover crops cultivated in autumn still showed a significant impact on maize yield, with common vetch (*Vicia sativa*, L.) as the most successful species. Interestingly, the effect of cover crop on weed cover and maize yield was not limited to the less intense strategy (no tillage). These results show that cultivating cover crops before maize in this type of conditions is a promising method to help controlling weeds. In addition, cover crops are known for providing multiple ecosystem services which could altogether improve the sustainability of cropping systems on the long term.

Keywords

no till, cover crop biomass, residue cover, integrated weed management

1 Introduction

Reduced tillage has gained popularity over the last thirty years among farmers. The occasional or systematic suppression of full-inversion ploughing implies an adaptation of the cropping system, notably in the control of weeds as well as of soil-borne organisms and pests (Lahmar, 2010; Peigné et al., 2007). Consequently, farmers using reduced tillage may choose to rely increasingly on herbicides and pesticides to deal with these threats (Lahmar, 2010). Weed control is currently identified as the main issue associated with reduced tillage and the key to sustainability (Bajwa, 2014; Eslami, 2014; Ramesh, 2015), especially in the context of conservation agriculture (Giller et al., 2009). The recent preoccupation concerning the toxicity of glyphosate (Braz-Mota et al., 2015; Gaupp-Berghausen et al., 2015; Sihtmäe et al., 2013), the main herbicide associated with reduced tillage (Nalewaja, 2003), requires new solutions to reduce its use and the appearance of resistances (Beckie, 2014; Nauen and Denholm, 2005; Walsh and Powles, 2014). In addition, the extensive reliance on herbicides in reduced tillage systems is particularly problematic in context where the cost of herbicides renders their access and use difficult or even impossible (Giller et al., 2009). Melander et al. (2013) and Nichols et al. (2015) discussed the perspective of adopting nonchemical weed management in reduced tillage systems by optimising crop rotation, cover crop use, stubble management, enhancement of crop growth and direct non-chemical methods.

The use of a cover crop between two cash crops brings together (i) soil cover as a living crop or a dead mulch and (ii) diversification of the crop rotation. Cover crops are expected to control weeds and may reduce the need to use herbicides (Alonso-Ayuso et al., 2018; Brust et al., 2014; Teasdale and Mohler, 2000). However, the beneficial effect of cover crops on weeds is generally linked to a high cover crop biomass or to a fast soil cover. If biomass and residues are scarce or rapidly decomposed, herbicides can then be needed, depending on weed pressure. Consequently, the choice of the best adapted cover crop species is crucial.

Cover crop species previously tested in reduced tillage systems were mainly wintering cover crop species (Carrera et al., 2004; Hayden et al., 2014; Mirsky et al., 2013; Sainju et al., 2002; Teasdale and Mohler, 1993; Williams et al., 1998). Non-wintering (i.e. frost-killed) species could be useful when the aim is to reduce simultaneously ploughing and herbicide use. Yet the practical issues are currently in the optimal combination of soil tillage intensity, herbicide timing/use and cover crop species choice. Consistent weeding practices based on annual weed pressure need to be studied to develop an integrated approach to control weeds.

The objective of this multi-year study is to highlight the contribution of a set of ten cover crop species to weed control and maize yield, in combination with two weeding strategies including no or minimum soil tillage, before a silage maize crop (*Zea mays*, L.). For this purpose, on-station field experiments were conducted during the period 2009-2014 in Switzerland, to investigate 1. the performance of cover crops in terms of biomass production in autumn and residue cover in early spring, 2. the influence of weeding strategies on weed cover in spring, 3. the effect of cover crops on weed cover within each weeding strategy, and 4. the effect of weeding strategies and cover crops on maize yield.

2 Materials and methods

2.1 Experimental setup

The experiments were set up at the research station Agroscope Changins (46° 24’ N, 06° 14’ E, 430 m above sea level), Switzerland, on a Cambisol (FAO classification). At this location, the average total annual precipitation is 999 mm and the mean air temperature 10.2°C (30-year averages, 1981-2010).

Four experiments were implemented, in 2009-2010 (hereafter named ‘year 0’), 2010-11 (‘year 1’), 2011-12 (‘year 2’) and 2013-14 (‘year 3’) on different fields at the same experimental station to study the influence of cover crops and weeding strategies on weed infestation and maize yield. Soil characteristics, crop management and observation dates for each experiment are presented in Supplementary Material Table S1. Each year, the experimental design corresponded to a strip plot with three replicates. Cover crop treatments represented the 'horizontal' factor of the strip plot, whereas weeding strategies represented the 'vertical' factor. Each unit plot (cover crop species x weeding strategy) had a size of 3 x 8 m.

Ten cover crop species (Table 1) and a no cover crop control were compared. The species list included three Brassicaceae species (Indian mustard, *Brassica juncea*, species code b1; turnip rape, *Brassica rapa campestris*, b2 and daikon radish, *Raphanus sativus longipinnatus*, b3), three Fabaceae species (field pea, *Pisum sativum*, f1; berseem clover, *Trifolium alexandrinum*, f2 and common vetch, *Vicia sativa*, f3), one Poaceae species (black oat, *Avena strigosa*, p1), two Asteraceae species (niger, *Guizotia abyssinica*, a1 and sunflower, *Helianthus annuus*, a2) and one Hydrophyllaceae species (phacelia, *Phacelia tanacetifolia*, h1). The cover crops were non-wintering species, known to grow well at this location. The control treatment was left non-seeded. In year 0, only seven of these ten cover crop species were tested (all species except daikon radish, common vetch and black oat, Table 1).

The second factor of the strip plot consisted in two different weeding strategies. The first, less intense one, involved no weeding (herbicide or tillage) interventions from cover crop seeding to maize seeding (1.NoTill). The second strategy involved minimum tillage (rotary harrow) prior to maize seeding. Herbicides (Dicamba, Terbuthylazine, Mesotrione, Nicosulfuron) were applied in all treatments at the end of May – beginning of June just after weed cover evaluation (Table S1), except in 2.MinTill in year 3 where a global very low weed infestation decided for the use of mechanical weeding instead of using herbicides. Figure 1 shows the timing of the weeding interventions.

2.2 Experiment management

All the experiments started in summer, after the harvest of the preceding crop. Deep inversion tillage (mouldboard plough, 20-30 cm depth) followed by rotary harrow (8 cm depth) was applied before cover crop seeding, except in year 3 where ploughing was not necessary, as a legume species and not a cereal was cultivated as preceding crop (rotary harrow only, 8 cm depth). Cover crops were seeded in mid-summer (end of July-beginning of August, Table S1), with an experimental seeder, at 2-3 cm depth. Cover crops were fertilised just after seeding with 30 kg N/ha, except in year 3 where the preceding crop was *Medicago sativa*, a legume species. The cover crops were shredded before maize seeding (horizontal axis shredder with hammer knives). Silage maize (cv. Ricardinio) was seeded in May - end of April in all plots with a pneumatic seeder, at a density of 10 plants/m^2, with an inter-row spacing of 0.75 m. Nitrogen fertilisation was applied twice, the first time in early May and then in early June (~120 kg N/ha in total).

2.3 Data collection

The aboveground biomass of the cover crops was evaluated each year at the end of the growing period (beginning of November, 96-97 days after seeding, Table S1), except for the first experiment in year 0, where no biomass sampling was done. Plants were collected at ground level in one 0.5 x 0.5 m quadrat from each plot. Biomass was then oven-dried at 60°C during 72 h and weighed to determine the aboveground dry matter of each cover crop species.

In early spring, the proportion of soil covered by the cover crops or their residues (when the cover crops were killed by frost) (abbreviated as 'residue cover' hereafter) was estimated visually in each plot, using a soil cover scale (example in Figure S2 in Büchi et al., 2018).

Soil coverage by weeds (abbreviated as 'weed cover' hereafter) was evaluated at the end of May, at the highly sensitive 2-4 leaf stage of maize (BBCH 12-14, 20-29 days after seeding), using the same method as for the cover crops.

Maize was harvested as whole plants with a combine harvester at the end of August – beginning of September (Table S1), except for the first experiment in year 0, where maize harvest was not conducted separately for each treatment. Fresh maize biomass was weighed and a subsample dried (72 h, 60°C) to determine its water content. The maize shoot dry yield (t/ha) was then calculated. Figure 1 shows the timing of these measurements in relation to crop management interventions.

2.4 Data analyses

The influence of cover crop species on biomass production and residue cover was tested independently each year using analyses of variance, followed by post-hoc Tukey HSD tests. Correlation between cover crop biomass and residue cover was tested using Kendall non-parametric correlation test.

The influence of the weeding strategies on weed cover and maize yield in the control plots without cover crop was tested independently each year using analyses of variance.

Independently for each year and each weeding strategy, the effect of cover crops on weed cover and maize yield, compared to the no cover crop control, was tested by analyses of variance followed by pairwise comparisons with least-square significant difference tests (R package "agricolae", de Mendiburu, 2017).

The contribution of cover crop biomass and residue cover to weed cover was analysed with multiple linear regressions. Correlation between weed cover and maize yield was tested using Kendall non-parametric correlation test. R 3.6.0 (R Core Team, 2019) was used to perform all statistical analyses.

3 Results

3.1 Cover crop biomass in autumn and residue cover in spring

For each year, average daily temperature was around 20°C at the beginning of the cover crop growth and decreased progressively to reach about 10°C at the beginning of November, when cover crop biomass was evaluated. During the cover crop growth period, between seeding and biomass sampling, the mean temperature was similar each year, around 15°C (14.4°C, 16.1°C, 14.9°C in year 1, year 2 and year 3). Growing degree days (GDD, with a base temperature of 0°C) were also quite similar between years, 1410, 1561 and 1461 GDD respectively. In contrast, the amount of rainfall between cover crop seeding and biomass sampling changed drastically between years, from 179 mm in year 1 and 209 in year 2 to 415 mm in year 3. Overall, cover crops produced about 4.7 t/ha aboveground biomass at the beginning of November (Table 2). Mean cover crop biomass was, on average, higher in year 3 compared to year 1 and year 2 (6.2 t/ha vs 3.7 and 4.2 t/ha, respectively). There was a significant interaction between year and cover crop species ($p<0.001$, Supplementary Material Figure S1) and so differences between cover crop biomass were tested independently each year (Table 2). General patterns of biomass production could nevertheless be identified (Table 2, Figure 2). At the beginning of November, sunflower (species code a2) showed, on average over the three years, the highest shoot dry matter among the tested species (8.7 t/ha). Niger (a1), the other Asteraceae, also presented high biomass (6.4 t/ha, 3-year average). Oat (p1), Indian mustard (b1) and phacelia (h1) performed rather well, with a 3-year average shoot dry matter between 4.8 and 5.6 t/ha. The three legume species (pea, f1; clover, f2 and vetch, f3), and the two Brassicaceae turnip rape (b2) and daikon radish (b3) presented the lowest 3-year average shoot dry matter (≤4.0 t/ha) (Table 2, Figure 2).

During winter, all cover crops were killed by frost except daikon radish and clover in year 3 due to insufficiently low temperatures. Overall, cover crop residue cover was around 44% in spring, but it varied between years and species (Figure 2, Table 2). The three legume species (f1, f2, f3) and oat (p1) showed the highest residue cover in early spring (≥ 55%, 3-year average, Table 2). Both Asteraceae (a1, a2) and phacelia (h1) showed intermediate soil cover (between 28 and 42%, 3-year average). The species with the lowest soil cover were the Brassicaceae (b1, b2, b3) species (≤13%, 3-year average).

Cover crop residue cover in early spring was not correlated with cover crop biomass in autumn (Kendall correlation coefficient $\tau = -0.04$, p-value = 0.748). Depending on the species characteristics, high residue cover in early spring could be achieved with low biomass in autumn, like for the three Fabaceae species (Figure 2). In contrast, sunflower produced high amount of biomass but resulting in low cover in spring, and the Brassicaceae species tended to produce low biomass and low residue cover (Figure 2).

3.2 Influence of weeding strategy on weed cover at early maize stage

Among the eight cases tested over the four years, only one (2.MinTill in year 3) led to a mean weed cover lower than the 5% threshold, and one had a mean weed cover around 10% (2.MinTill in year 1) (Figure 3A). The six other strategies showed higher weed cover (>40%, Figure 3A and Supplementary Material Table S2). The less intense weeding strategy (1.NoTill), involving no tillage prior to maize seeding can be used as an indicator of overall weed pressure. Without any weeding intervention, weed cover after maize seeding ranged from 43% in year 2 up to 90% in year 0. Compared to this low intensive weeding strategy, the other weeding strategy gave contrasting results for each year (Figure 3A). In years 0 and 2, no significant effect of the tillage before maize seeding on the weed cover was observed, whereas in years 1 and 3 a highly significant reduction of weed cover was observed, allowing to decrease weed pressure to around or less than 10%.

3.3 Influence of cover crops on weed cover at early maize stage

Comparing the weed cover in the cover crop treatments and in the control with no cover crop allows to highlight the potential of cover crops to reduce weed pressure at early maize stage (2-

4 leaf stage) (Figure 3B and Supplementary Material Table S2). It was expected that the more pronounced cover crop impact would be observed in the less intense weeding strategy (1.NoTill), where no tillage was applied. This was however not systematically the case. No effect of cover crops compared to the control could be observed in years 0 and 1 (Figure 3B). In year 2, all species induced a significant reduction of weed cover except clover f2, vetch f3 and oat p1. In year 3, niger a1 and oat p1 allowed a reduction of weed cover, from 62% (control) to 11% for oat.

In the strategy involving minimum tillage before maize seeding (2.MinTill), a significant effect of cover crops could still be observed despite this late tillage intervention, except in year 3 where the no cover crop control was at only 3% weed cover (Figure 3B). Four cover crop species always induced a significant reduction of weed cover at early maize stage in this strategy: field pea f1, niger a1, sunflower a2 and phacelia h1.

When looking at the cover crop species which systematically allowed to reducing weed cover across years and strategies, the most successful species was niger a1, followed by field pea f1, sunflower a2 and phacelia h1 (Figure 3B).

Cover crop biomass production in autumn and residue cover in spring did not, in general, explain the weed cover observed in early spring for most of the strategies. These two variables accounted for a significant part of the variance in weed cover, but with really low R^2, only in year 2 (1.NoTill: $R^2 = 24\%$ and 2.MinTill: $R^2 = 34\%$, $p<0.05$). Residue cover alone appeared to have a significant effect in year 3 for the less intense strategy (1.NoTill: $R^2 = 16\%$, $p<0.05$).

3.4 Influence of tillage and cover crops on maize yield

Across years 1, 2 and 3, the mean maize yield in the no cover crop control ranged from 11.3 t/ha to 16.9 t/ha (Figure 4A). A significant difference between the two weeding strategies was observed only in year 1, with 13.5 t/ha in 1.NoTill and 16.9 t/ha in 2.MinTill. Significant differences between some cover crop species and the no cover crop control could be observed for maize yield in four out of the six cases (Figure 4B and Supplementary Material Table S3), but generally cover crop treatments show yield similar to the control. In year 1, where a significant reduction of maize yield in the 1.NoTill strategy could be observed in the absence of cover crops, some cover crop species allow to reach a yield similar to that observed in the 2.MinTill strategy (Figure 4B).

Vetch f3 was the species appearing most often (three times) as allowing to improve yield compare to the no cover crop control, followed by field pea f1, oat p1 and niger a1 (twice each) (Figure 4B). Significant negative correlations between maize yield and weed cover at early maize stage was observed in three out of six cases (1.NoTill in year 1 and 3, 2.MinTill in year 3), despite all treatments having been weeded in between weed cover estimation and maize harvest.

4 Discussion

4.1 Influence of weeding strategy on weed infestation and maize yield

Comparing the weed cover observed in the weeding strategies involving minimum tillage to that without tillage highlighted a high inconsistency in the efficiency of this method. Only in 50% of the cases (two out of four cases), the use of tillage allowed to reduce significantly the weed cover in the no cover crop controls, compared to the strategy with no intervention. Tillage before maize seeding can disrupt standing weeds and thus control their proliferation, but at the same time the soil loosening may also recruit weed seeds from the soil seedbank (and in particular *Echinochloa crus-galli* in these experiments) and give them favourable emergence conditions (Nichols et al., 2015, Sadeghpour et al., 2014). Therefore, depending on the weather conditions, minimum tillage before maize seeding is not sufficient to prevent weed emergence. Despite the herbicide application in all treatments just after weed cover evaluation, maize yield in the control with no cover crop still shows a pattern mirroring the pattern observed for weed cover, with higher yield in the minimum tillage compared to the no till strategy when the weed cover at early maize stage was significantly reduced. This confirms the observation that maize performance is highly sensitive to weed infestation in early stages (Page et al., 2012).

4.2 Cover crop performance and effect on weed infestation and maize yield

Cover crop biomass production varied between years, partly as a response to rainfall amount during cover crop growth. For most species, the biomass produced in three months of growth was higher than 3 t/ha, previously identified as a threshold for good cover crop performance (Gfeller et al., 2018; Wendling et al., 2019). Only turnip rape and daikon radish in years 1 and 2 failed to reach this threshold, with a mean biomass lower than 3 t/ha (between 1.2 and 1.6 t/ha).

Cover crops induced a reduction of weed infestation at the early stage of maize in most of the situations, even when tillage was applied after cover crop cultivation. However, the presence or magnitude of infestation reduction was not easily predicted based on the data collected in this study. It is generally admitted that high biomass production or good soil cover are the key characteristics allowing an efficient weed control by cover crops (Brust et al., 2014, Buchanan et al., 2016). However, an influence of species identity, and of the use of mixtures, has also been demonstrated (Baraibar et al., 2018).

Different factors could explain why cover crops are generally associated with weed control (Dorn et al., 2015; Kruidhof et al., 2008; Weber et al., 2017). As living crops, they modify environmental conditions to the detriment of weeds or directly compete with them for resources (Rueda-Ayala et al., 2015; Smith et al., 2015). As dead mulches, they physically constrain weed seedling emergence (Teasdale and Mohler, 2000), by reducing light transmittance to the soil, soil maximum temperature and daily soil temperature amplitude (Teasdale and Mohler, 1993). Additionally, cover crop residues can improve the environmental conditions for the growth of seed predators or soil fauna which may destroy or degrade seeds, but field studies have reported contradictory results (Nichols et al., 2015). Living or dead, cover crops may express allelopathy (Farooq et al., 2013; Gfeller et al., 2018). The diversity of the cover crop species tested and the variability of weed responses illustrates the many factors involved and the uncertain outcome according to the context.

In this study, despite high variability between years, some cover crop species systematically allowed to reduce weed infestation. The Asteraceae species (niger and sunflower*)* produced large amounts of biomass during each year of experiment and generally showed good weed control, and appear in some cases to improve maize yield. This performance may rely on their competitiveness as living plants against autumn germinating weeds and as dead mulch against spring germinating weeds, especially when shredded residues were left on the soil surface. In case of soil tillage before maize seeding, the incorporation of high amounts of carbon-rich and slowly mineralizable residues may have disturbed weed emergence through nitrogen immobilization (Justes et al., 2009) or the creation of a physical barrier (Kruidhof et al., 2008). Sunflower is also known to express allelopathy against weeds and to improve subsequent wheat growth (Alsaadawi et al., 2012).

Among the legume species, field pea and common vetch gave good soil cover at the end of winter despite medium to low shoot growth during autumn. These legumes were the only cover crop species with a creeping growing habit compared to the other tested species, which had a more erected architecture. A long-lasting good soil cover could partly explain the successful weed control of these species. However, common vetch failed to control weeds and was often among the less efficient species, together with berseem clover, which had a more erected architecture. Isik et al. (2009) also observed that berseem clover was the worst species in the control of weeds when used as cover crop before spring planted sweet pepper. Despite the deficient weed control by common vetch, this species shows a positive effect on maize yield in three cases, which can be probably explained by a beneficial input of nitrogen from this legume species. No assessment of nitrogen concentration in the cover crops were made in this study, but an experiment on biological nitrogen fixation conducted in a neighbouring field in the year

2011-2012 allowed to highlight the huge amount that legume cover crops can accumulate in only three months of growth (Büchi et al., 2015). Using the values of nitrogen fixation from this previous study combined with the biomass observed in the current study, it can be estimated that common vetch could have accumulated about 121 kgN/ha of nitrogen on average. Meanwhile, the estimates for field pea would be only 67 kgN/ha and 42 kgN/ha for berseem clover.

The three Brassicaceae species were characterized by intermediate to low biomass in autumn and really low residue cover in spring, and consequently did not achieved good weed control, despite potential allelopathic effects (Bangarwa and Norsworthy, 2014; Haramoto and Gallandt, 2005).

Black oat froze and lodged during winter, providing a thick soil cover despite intermediate growth compared to other cover crop species. Grimmer and Masiunas (2004) made a similar observation with *Avena sativa*. The good weed control of this grass in years 1 and 3 can thus be linked to the good soil cover during winter. In year 3, oat was the most efficient species against weeds in the less intensive weeding strategy (1.NoTill), and induced a really high maize yield afterwards.

Finally, phacelia presented an intermediate performance both in biomass production and residue cover, and was generally efficient in terms of weed control but did not appear to improve maize yield.

Overall, an increase of maize yield associated with the overall improvement of soil quality and fertility induced by the use of cover crops could have been expected (Fageria et al., 2005). However, in these experiments, the maize fertilisation level was as recommended and could have thus reduced the potential differences between cover crop species, and in particular the distinction of legume versus non legume species. In addition, the weeding intervention in the early maize could have cancelled some of the residual effect of cover crop species on weed infestation. Future experiments should thus be conducted in less optimal conditions, poorer soil, less fertilisers, challenging weather conditions, to reveal further the potential of cover crops to maintain maize yield. This would be of particular relevance in contexts where the access and price of herbicides do not allow to rely on these inputs, and thus where weed control is crucial to insure sufficient yield and sustainability of the system, such as in Sub-Saharan Africa.

5 Conclusions

Overall, the application of tillage prior to maize seeding did not always guarantee a low weed cover in the early stage of maize growth. In most cases, the cultivation of non-wintering cover crops species before maize seeding allowed to reduce weed infestation, down to only 15% weed cover in a lot of cases. The most efficient cover crop species for weed control varied from year to year, but niger, sunflower, field pea and phacelia gave the best results throughout the experiments. An effect of cover crops on maize yield could still be observed in some situations. Therefore, the use of cover crops is recommended to limit weed incidence and improve yield. Besides weed control, cover crops also provide other ecosystem services, such as soil protection during winter, nitrogen recycling or auxiliary insect promotion. However, as trade-offs between these services exist, cultivation of cover crop species mixtures may offer a solution for accumulating multiple and complementary services.

Acknowledgements

The authors wish to thank Cindy Bally, Nicolas Widmer and all the persons who helped with the management of experiments and data collection, and Jonne Rodenburg for help and comments on previous versions of the manuscript. We also thank the two anonymous reviewers who provided valuable comments on a previous version of this manuscript. This study was partly funded by the Swiss National Science Foundation in the framework of the

National Research Program NRP 68 ‘Sustainable Use of Soil as a Resource’ [grant 406840-143063].

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Table and figure captions

Table 1 Name, botanical family, code and seeding rate for the ten cover crop species.

Table 2 Mean dry biomass of cover crops (t/ha) in autumn, and residue cover (%) in early spring for the three year of experiment with biomass/cover estimation. Within each column, values with the same letters are not significantly different (Tukey HSD test, $p<0.05$).

Figure 1 Schematic representation of the implemented weeding strategies and observations for the four years of experiment.

Figure 2 Relative values (to the yearly average of all ten cover crop species values) of biomass production in autumn and residue cover in early spring for the ten cover crop species, for the three years of experiment with biomass/cover estimation.

Figure 3 Weed cover [%] at early maize stage. A. No cover crop control plots. Different letters indicate significant differences ($p<0.05$) between weeding strategies, within each year. B. Cover crop treatment plots. The solid horizontal black lines show the mean weed cover in the respective no cover crop controls (i.e. mean values of the boxplots shown in panel A). Cover crop species showing significantly different weed cover than the control are indicated with the code of the species name, non significant ones are shown with a circle. The horizontal dotted line shows the 5% threshold.

Figure 4 Maize yield (dry silage) [t/ha]. A. No cover crop control plots. Different letters indicate significant differences ($p<0.05$) between weeding strategies, within each year. B. Cover crop treatment plots. The solid horizontal black lines show the mean maize yield in the respective no cover crop controls (i.e. mean values of the boxplots shown in panel A). Cover crop species showing significantly different weed cover than the control are indicated with the code of the species name, non significant ones are shown with a circle.

Supplementary Material

Table S1 Soil characteristics, crop management and observation dates for each year of experiment

Table S2 Mean and standard error of weed cover at early maize stage (2-4 leaf stage) for each cover crop treatment, weeding strategy and year of experiment.

Table S3 Mean and standard error of maize yield for each cover crop treatment, weeding strategy and year of experiment.

Figure S1 Cover crop biomass in autumn (A.) and residue cover in spring (B.) for each year of experiment.

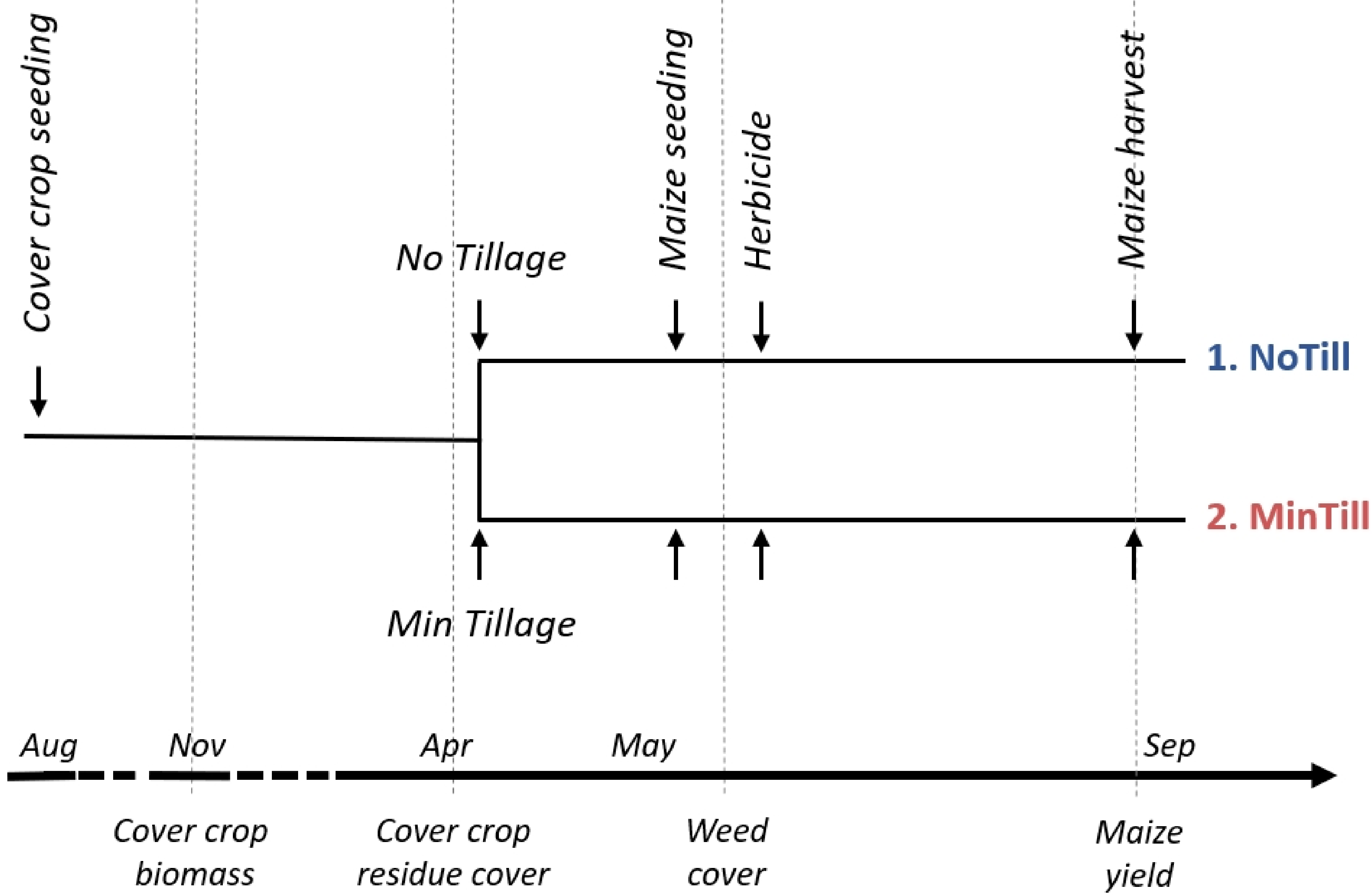
Table 1

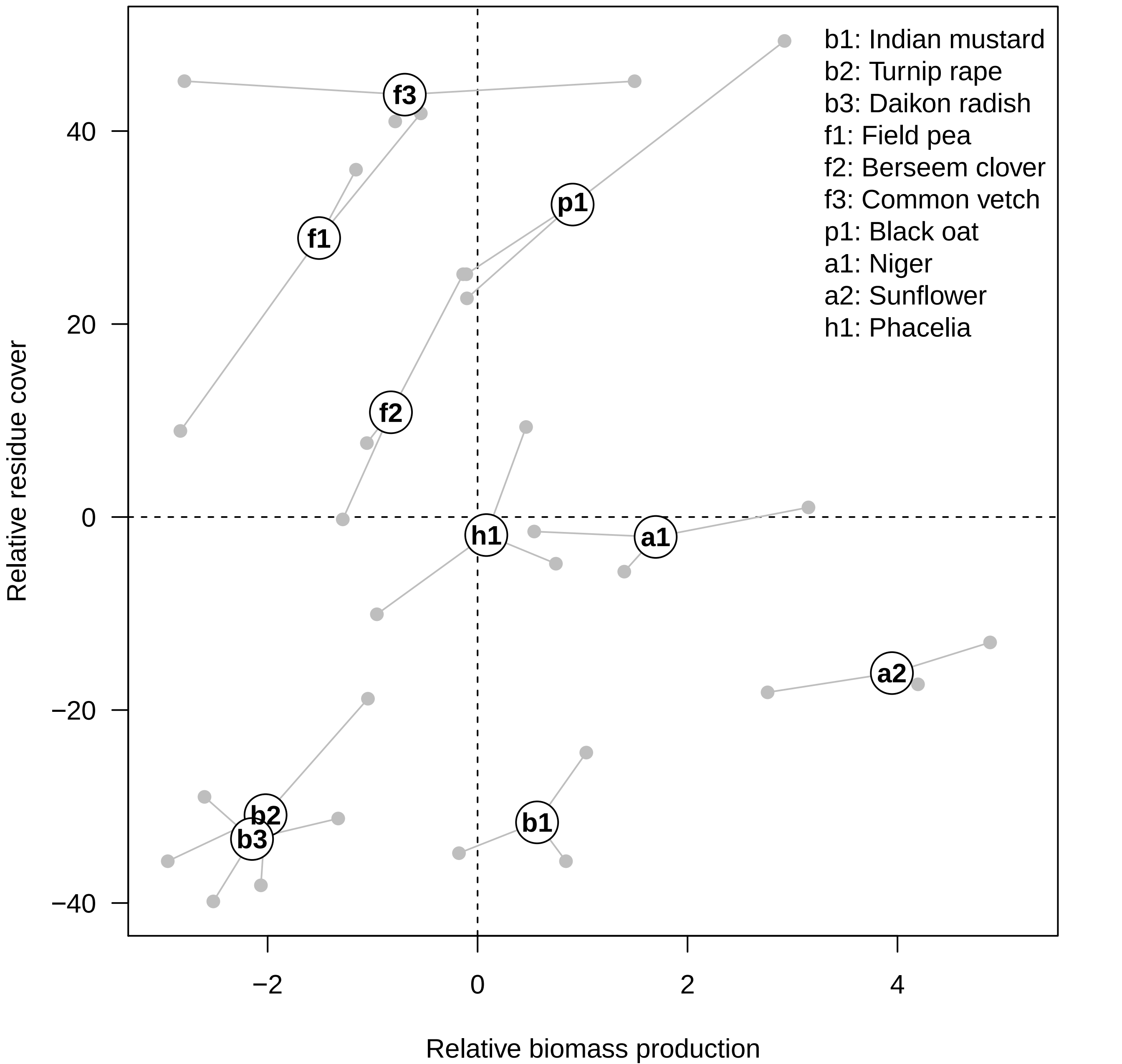
Latin name	Common name	Family	Code	Mean seeding rate
				grain/m2
Brassica juncea, (L.) Czern.	Indian mustard	Brassicaceae	b1	515
Brassica rapa L., var *campestris*	Turnip rape	Brassicaceae	b2	630
Raphanus sativus L., var *longipinnatus*	Daikon radish*	Brassicaceae	b3	110
Pisum sativum, L.	Field pea	Fabaceae	f1	135
Trifolium alexandrinum, L.	Berseem clover	Fabaceae	f2	605
Vicia sativa, L.	Common vetch*	Fabaceae	f3	225
Avena strigosa, Schreb.	Black oat*	Poaceae	p1	490
Guizotia abyssinica, (L.f.) Cass.	Niger	Asteraceae	a1	270
Helianthus annuus, L.	Sunflower	Asteraceae	a2	75
Phacelia tanacetifolia, Benth.	Phacelia	Hydrophyllaceae	h1	450

* these three species were not tested in year 0

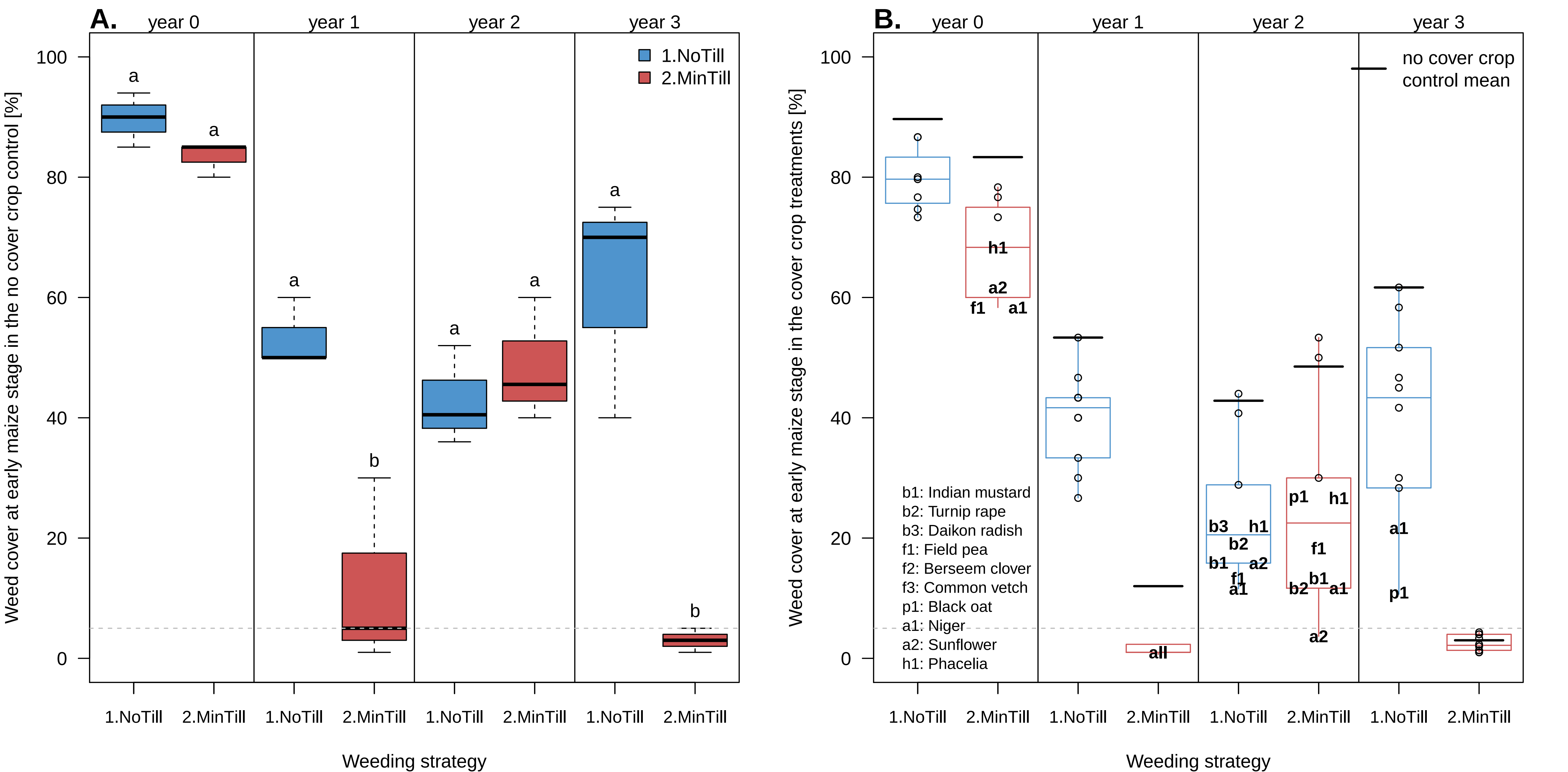
Table 2

Species		Dry biomass [t/ha]							Residue cover [%]						
		year 1		year 2		year 3		*mean*	year 1		year 2		year 3		*mean*
b1	**Indian mustard**	3.5	bc	5.1	bc	7.3	bc	*5.3*	10	de	15	f	13	de	*13*
b2	**Turnip rape**	1.6	cd	1.3	d	5.2	cd	*2.7*	7	e	15	f	18	cde	*13*
b3	**Daikon radish**	1.2	d	1.6	d	4.9	cd	*2.6*	5	e	22	ef	6	e	*11*
f1	**Field pea**	3.2	bcd	3.1	cd	3.4	d	*3.2*	87	a	87	ab	46	b	*73*
f2	**Berseem clover**	3.6	bc	3.2	cd	5.0	cd	*3.9*	70	ab	58	cd	37	bc	*55*
f3	**Common vetch**	5.2	ab	3.4	cd	3.4	d	*4.0*	90	a	92	a	82	a	*88*
p1	**Black oat**	3.6	bc	4.1	cd	9.2	ab	*5.6*	70	ab	73	bc	86	a	*77*
a1	**Niger**	4.2	b	7.4	ab	7.6	bc	*6.4*	43	bc	52	d	31	bcd	*42*
a2	**Sunflower**	6.5	a	8.4	a	##	a	*8.7*	27	cde	33	e	24	bcde	*28*
h1	**Phacelia**	4.5	ab	4.7	bc	5.3	cd	*4.8*	40	bcd	60	cd	27	bcde	*42*
	mean	*3.7*		*4.2*		*6.2*		*4.7*	*45*		*51*		*37*		*44*

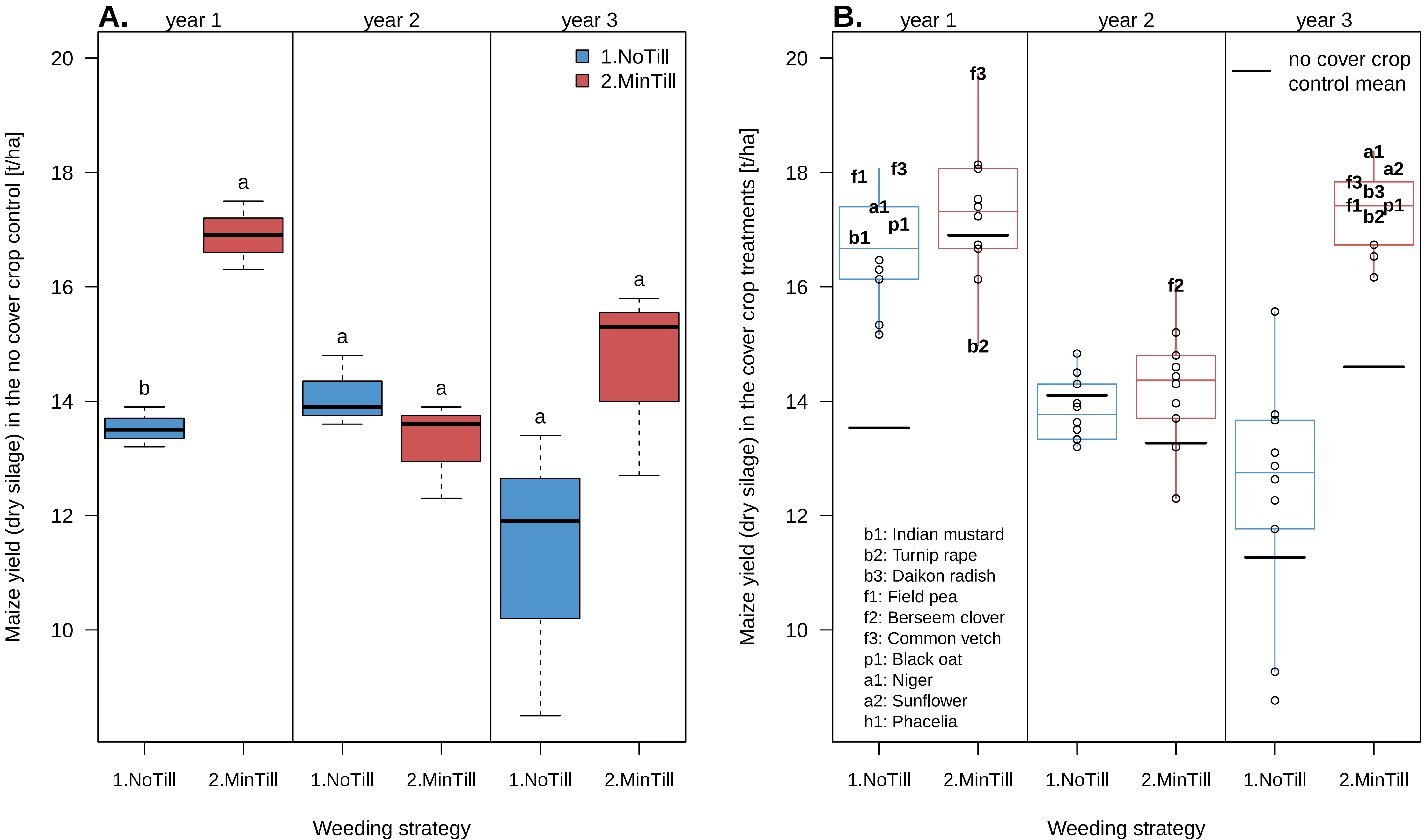

Cover crop seeding
No Tillage
Maize seeding
Herbicide
Maize harvest
1. NoTill
2. MinTill
Min Tillage
Aug
Nov
Apr
May
Sep
Cover crop biomass
Cover crop residue cover
Weed cover
Maize yield



b1: Indian mustard
b2: Turnip rape
b3: Daikon radish
f1: Field pea
f2: Berseem clover
f3: Common vetch
p1: Black oat
a1: Niger
a2: Sunflower
h1: Phacelia
f3
f1
p1
f2
h1
a1
a2
b2
b3
b1
40
20
0
−20
−40
−2
0
2
4
Relative residue cover
Relative biomass production



A.
year 0
year 1
year 2
year 3
1.NoTill
2.MinTill
Weed cover at early maize stage in the no cover crop control [%]
Weeding strategy
B.
no cover crop control mean
Weed cover at early maize stage in the cover crop treatments [%]
b1: Indian mustard
b2: Turnip rape
b3: Daikon radish
f1: Field pea
f2: Berseem clover
f3: Common vetch
p1: Black oat
a1: Niger
a2: Sunflower
h1: Phacelia
all
Weeding strategy



A.
year 1
year 2
year 3
1.NoTill
2.MinTill
Maize yield (dry silage) in the no cover crop control [t/ha]
10
12
14
16
18
20
a
b
a
a
a
a
1.NoTill
2.MinTill
1.NoTill
2.MinTill
1.NoTill
2.MinTill
Weeding strategy
B.
year 1
year 2
year 3
no cover crop
control mean
Maize yield (dry silage) in the cover crop treatments [t/ha]
f1
f3
a1
p1
b1
f3
b2
f2
a1
a2
f3
b3
f1
p1
b2
b1: Indian mustard
b2: Turnip rape
b3: Daikon radish
f1: Field pea
f2: Berseem clover
f3: Common vetch
p1: Black oat
a1: Niger
a2: Sunflower
h1: Phacelia
1.NoTill
2.MinTill
1.NoTill
2.MinTill
1.NoTill
2.MinTill
Weeding strategy

Table S1 Soil characteristics, crop management and observation dates for each year of experiment.

Experiment	year 0 2009-2010	year 1 2010-2011	year 2 2011-2012	year 3 2013-2014
Soil characteristics				
Clay (%)	26.2	24.6	32.1	26.1
Sand (%)	31.6	29.7	34.1	28.5
USDA texture	Loam	Loam	Clay loam	Loam
pH	8.0	7.7	7.3	7.4
Organic matter (%)	2.1	1.9	3.2	2.4
Cover crop and maize management				
Cover crop seeding	31.07.2009	29.07.2010	29.07.2011	06.08.2013
Cover crop residue shredding	25.05.2010	04.05.2011	03.04.2012	05.05.2014
Cover crop residue harrowing*	25.05.2010	04.05.2011	30.04.2012	05.05.2014
Maize seeding	26.05.2010	04.05.2011	30.04.2012	06.05.2014
Herbicide	-	28.05.2011	26.05.2012	03.06.2014
Maize harvest	-	06.09.2011	23.08.2012	12.09.2014
Observation dates				
Cover crop biomass [DAS]	-	03.11.2010 [97]	02.11.2011 [96]	11.11.2013 [97]
Cover crop residue cover	-	04.05.2011	03.04.2012	19.03.2014
Weed cover (2-4 leaf stage of maize) [DAS]	24.06.2010 [29]	27.05.2011 [23]	25.05.2012 [25]	26.05.2014 [20]

* Only on the respective treatments (see Figure 1)

Table S2 Mean and standard error of weed cover at early maize stage (2-4 leaf stage) for each cover crop treatment, weeding strategy and year of experiment.

Mean weed cover [%] +- 1*se

Species		year 0				year 1				year 2				year 3			
		1. NoTill		2. MinTill		1. NoTill		2. MinTill		1. NoTill		2. MinTill		1. NoTill		2. MinTill	
b1	**Indian mustard**	87	4.4	77	3.3	43	8.8	2	1.5	16	4.0	13	4.4	58	13	4	3.0
b2	**Turnip rape**	87	3.3	73	6.0	40	5.8	1	0.3	19	0.1	12	4.4	45	16	3	1.9
b3	**Daikon radish**					40	10.0	1	0.0	22	1.5	30	10.0	28	4	1	0.3
f1	**Field pea**	75	14.1	58	12.0	33	6.7	2	1.3	13	6.2	18	6.0	42	16	2	0.3
f2	**Berseem clover**	80	10.1	78	1.7	47	12.0	1	0.0	41	2.2	50	11.5	52	10	4	1.5
f3	**Common vetch**					30	10.0	1	0.0	44	10.6	53	13.3	30	10	1	0.0
p1	**Black oat**					43	13.3	2	1.3	29	4.7	27	3.3	11	5	1	0.0
a1	**Niger**	73	1.7	58	4.4	27	3.3	2	1.3	12	3.9	12	3.3	22	7	1	0.3
a2	**Sunflower**	80	2.9	62	1.7	43	20.3	1	0.0	16	6.1	4	1.3	47	9	2	0.6
h1	**Phacelia**	77	8.8	68	1.7	53	13.3	1	0.0	22	1.5	27	7.3	62	14	4	1.8
	no cover crop control	90	2.6	83	1.7	53	3.3	12	9.1	43	4.8	49	6.0	62	11	3	1.2
	mean	*81*		*70*		*41*		*2*		*25*		*27*		*42*		*3*	

Table S3 Mean and standard error of maize yield for each cover crop treatment, weeding strategy and year of experiment.

Mean maize yield [t/ha] +- 1*se

Species		year 1					year 2					year 3			
		1. NoTill		2. MinTill			1. NoTill		2. MinTill			1. NoTill		2. MinTill	
b1	Indian mustard	16.9	1.2	17.2	0.5		13.3	0.5	14.3	0.2		12.3	0.7	16.2	0.6
b2	Turnip rape	16.1	1.6	15	0.4		13.2	0.4	12.3	0.4		13.8	0.9	17.2	1.5
b3	Daikon radish	16.5	0.3	16.1	0.6		14.3	0.6	15.2	1.3		12.6	0.5	17.7	0.4
f1	Field pea	17.9	1.1	18.1	0.0		13.9	0.2	13.7	0.6		12.9	0.6	17.4	0.5
f2	Berseem clover	15.3	1.0	18.1	0.6		14	0.8	16	1.6		9.27	3.1	16.7	1.0
f3	Common vetch	18.1	0.8	19.7	0.3		13.5	0.6	14.6	0.8		13.7	0.3	17.8	0.7
p1	Black oat	17.1	1.5	16.7	0.0		13.3	0.6	14.4	0.5		15.6	0.1	17.4	0.4
a1	Niger	17.4	1.1	16.7	0.1		13.6	1.0	14	0.2		13.1	1.4	18.4	1.2
a2	Sunflower	16.3	0.5	17.4	0.7		14.5	0.7	14.8	1.1		11.8	0.9	18.1	0.6
h1	Phacelia	15.2	0.6	17.5	0.4		14.8	1.0	13.2	0.5		8.77	3.3	16.5	0.5
	no cover crop control	13.5	0.2	16.9	0.3		14.1	0.4	13.3	0.5		11.3	1.4	14.6	1.0
	mean	*16.4*		*17.2*			*13.9*		*14.2*			*12.3*		*17.1*	

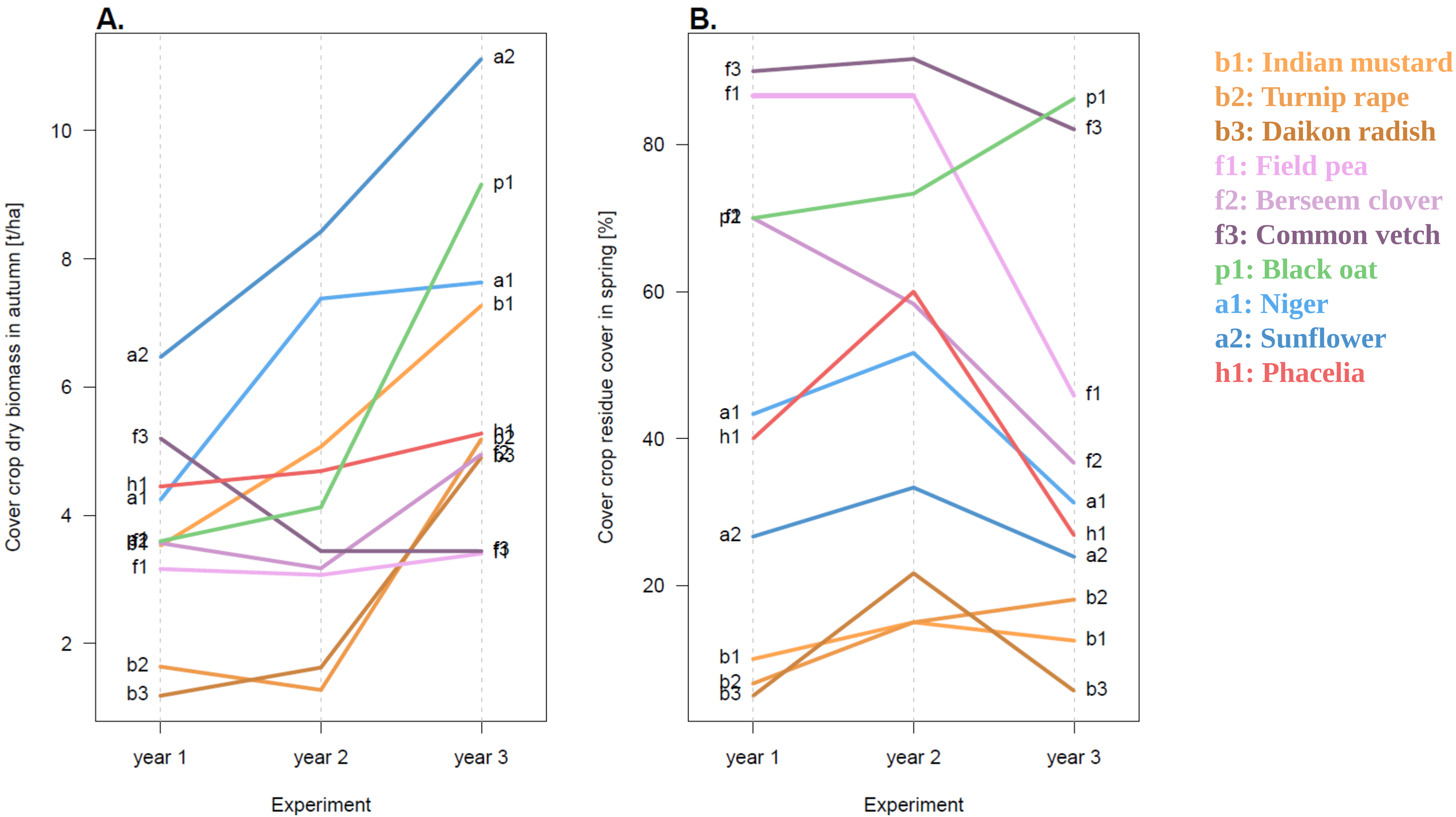


Figure S1 Cover crop biomass in autumn (A.) and residue cover in spring (B.) for each year of experiment.