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## Article

# Management Effect on the Weed Control Efficiency in Double Cropping Systems

Fruzsina Schmidt <sup>1,\*</sup>, Herwart Böhm <sup>2</sup>, Rüdiger Graß <sup>1</sup>, Michael Wachendorf <sup>1</sup> and Hans-Peter Piepho <sup>3</sup>

<sup>1</sup> Grassland Science and Renewable Plant Resources, Faculty of Organic Agricultural Science, Universität Kassel, Steinstraße 19, 37213 Witzenhausen, Germany

<sup>2</sup> Institute of Organic Farming, Johann Heinrich von Thünen Institute, Federal Research Institute for Rural Areas, Forestry and Fisheries, Trenthorst 32, 23847 Westerau, Germany

<sup>3</sup> Biostatistics Unit, Institute of Crop Science, Universität Hohenheim, Fruwirthstraße 23, 70599 Stuttgart, Germany

\* Correspondence: fruzsina.schmidt@uni-kassel.de; Tel.: +49-561-804-1339

**Abstract:** There are often negative side-effects associated with the traditional (silage) maize cropping system related to the unprotected soil surface. Reducing soil disturbance could enhance system sustainability. Yet, increased weed pressure and decreased nitrogen availability, particularly in organic agriculture, may limit the implementation of alternative management methods. Therefore, a field experiment was conducted at two distinct locations to evaluate the weed control efficiency of 18 organically managed silage maize cropping systems. Examined parameters were relative weed groundcover ( $GC_{weed}$ ) and its correlation with maize dry matter yield (DMY), relative proportion of dominant weed species (DWS) and their groups by life form ( $DWS_{group}$ ). Treatment factors comprised *first crop* (FC—winter pea, hairy vetch, and their mixtures with rye, control (sole silage maize cropping system—SCS)), *management*—incorporating FC use and tillage (double cropping system no-till (DCS NT), double cropping system reduced till (DCS RT), double cropped, mulched system (DCMS Roll) and SCS control), *fertilization*, *mechanical weed control* and *row width* (75 cm and 50 cm). The variation among environments was high, but similar patterns occurred across locations: Generally low  $GC_{weed}$  occurred (below 28%) and, therefore, typically no correlation to maize DMY was observed. The number of crops (*system*), *system:management* and occasionally *management:FC* (*group*) influenced  $GC_{weed}$  and  $DWS_{(group)}$ . *Row width* had inconsistent and/or marginal effects. Results suggest differences related to the successful inclusion of DCS and DCMS into the rotation, and to the altered soil conditions, additional physical destruction by shallow tillage operations, especially in the early season, which possibly acts through soil thermal and chemical properties, as well as light conditions. DCS RT could successfully reduce  $GC_{weed}$  below 5%, whereas DCS NT and particularly DCMS (Mix) suffered from inadequate FC management. Improvements in DCMS may comprise the use of earlier maturing legumes, especially hairy vetch varieties, further reduction/omission of the cereal companion in the mixture and/or more destructive termination of the FC.

**Keywords:** organic agriculture; winter cover crop; silage maize; roller-crimper; tillage; row width; relative species abundance



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## 1. Introduction

Silage maize production in Germany is at a continuously high level [1,2]. However, concerns about system sustainability are rising due to negative side effects associated with traditional maize production.

In temperate European conditions, under old/traditional organic management, the row crop maize is usually sown in early May, mostly with 75 cm row width into an autumn-ploughed soil (CT), often after a winter fallow. The crop has a high nitrogen (N) and temperature demand, a slow juvenile development, and therefore, a low competitive

ability in the early season. Consequently, from the harvest operations/incorporation of the residues of the previous crop—be it a cover crop or not—until canopy closing of the maize crop (late June–July), the system leaves most of the soil surface open [3], which in turn increases the soil erosion risk and offers an open niche to weeds [4–8]. Thus, a series of intensive mechanical weed control operations are usually conducted [5,7], which further accelerates the soil erosion risk and increases the soil compaction risk [7,9]. Climate change may enhance these problems due to more variable local climates and the increased chance of weather extremes [10–14]. These difficulties are even more pronounced in organic agriculture, where tillage and mechanical weed control—also tightly connected to nutrient management—are an essential part of the (silage) maize production. The demand to reduce the tillage-based management in at least some phases of the crop rotation also reached the organic farming community [5,7]. A possible reduction of tillage practices at very demanding phases of the rotation—e.g., with row crops such as (silage) maize—may thus result in ecological benefits for the farming system [9].

Intending to reduce soil disturbance—partially related to mechanical weed control—several alternative systems have emerged. Some reduce the wide row width to accelerate the canopy closing [4,15,16]. Others use a winter cover crop [5,17], which may increase soil protection and weed control, while potentially reducing nutrient losses over the winter months [6,7]. Afterwards, the cover crop may be harvested (classical double cropping systems (DCS)) or it may be mulched to support the following maize crop (double cropped, mulched system—DCMS). Such alternative systems most often utilize cereals, legumes and their mixtures to balance the possible benefits and setbacks—e.g., nutrient, especially N dynamics, or soil cover [1,18–22]. In DCS, the tillage type after the cover crop harvest may further influence nutrient and weed management [7,17,23–27]. In DCMS, the soil is protected at least until the early development phase of the second crop [28]. The residue quality and quantity will determine the potential success of DCMS systems—e.g., plant available water and nutrients, especially N dynamics, cover crop regrowth and the success of maize sowing and development, along with the length of the vegetative window [3,8,19,21,22,28–37]. Under German conditions, leafy, wild-type winter pea, hairy vetch [3,21,28] and rye—alone or as a cereal companion—showed promising results [1,28].

Most of the research under organic conditions—comparing some of these alternative systems—concluded that the main challenge in organic (silage) maize production remains the weed management, which may hinder soil conservation practices [5,7]. Furthermore, weather and environment strongly influence the system-related possibilities/effects of weed management and crop yield development [4,5,24,25]. The researchers in the mentioned sources highlighted the importance of understanding the systems and interactions within.

For efficient weed control, not just the amount of weeds, but also the community itself is decisive [26,38]. Some recent comprehensive surveys on weed communities in maize cropping systems across Germany revealed that weed species most commonly associated with maize cropping—summer annuals such as *Solanum nigrum* L., *Amaranthus* spp.—are rather scarce, whereas other, more generalist species dominate the weed flora on many maize fields [39–42]. This could be partially due to the chosen methodology of early weed survey in maize BBCH 12–18 [39,41,42], as pointed out by Mehrtens et al. [41]. De Mol et al. [39] examined factors which could potentially shape the weed communities. They revealed similar results as previous examinations in other studies that the chosen characteristics (factors) fail to explain most of the variation. Nevertheless, from the amount of variation explained, environment—especially *location*, *location:climate* and *location:soil* interactions—had the strongest effect, whereas management could explain only a comparatively small amount of variation—mostly by *rotation* and, to a smaller extent, by *tillage*. *Year* had only a marginal effect on weed composition [39]. Similar results on the influence of *rotation* and *tillage* were found for community-averaged weed traits [43–45].

The cited research included some alternative systems (DCS and DCMS) with a special focus on weed control, whereas others surveyed maize fields under a broad range of management conditions. Only a few articles reported factor effects on weed com-

munities as a whole—e.g., [38,40,41]—rather than focusing on one or a couple of weed species—e.g., [31,32,46,47]—or purely on weed biomass, density, diversity indices or community-averaged weed traits to describe the community under different management conditions—e.g., [6,23,43–45].

An exact field experiment was conducted to assess management effects and their interactions on maize yield and weed development. Here, various combinations of tillage-reduced weed management were compared at two locations over two years. The study aimed to compare alternative management systems—different winter cover crops, *management* (DCS with RT or NT, DCMS) and *row width*—to a sole silage maize cropping system (SCS) [3].

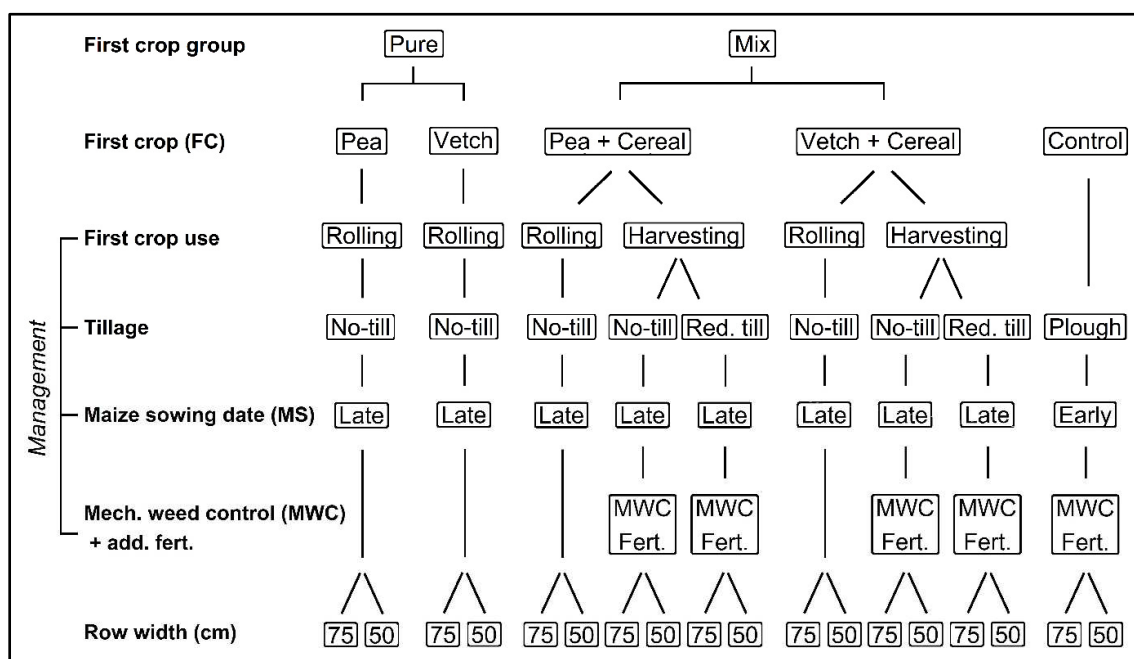
The focus of this article lies on the relative weed control efficiency—groundcover ( $GC_{weed}$ ), dominant weed species (DWS) and their groups by life form ( $DWS_{group}$ ). The objectives of the analysis are to measure the main factor effects (*FC*, *management* and *row width*) and to help the understanding of guiding principles by evaluating interactions among treatment factors and with localities. The following major hypotheses were defined for the study: Under organic management and during the vegetative maize development phase, (1)  $GC_{weed}$  in DCS and DCMS is comparable to SCS; (2)  $GC_{weed}$  is strongly influenced by *tillage* with the expected pattern DCMS < DCS RT < DCS NT; (3) similarly,  $GC_{weed}$  is lower in DCMS with legume–cereal mixtures than in DCMS with pure legume stands; and (4)  $GC_{weed}$  is reduced with reduced row width, irrespective of other factors. Additionally, (5)  $GC_{weed}$  reduces maize dry matter yield and finally, (6)  $DWS_{(groups)}$  are altered by DCS and DCMS compared with SCS.

## 2. Materials and Methods

A field experiment was conducted at two German locations (Trenthorst, Schleswig-Holstein (TRE, N 53.76667 E 10.51667, 40 m above sea level (ASL)) and Neu-Eichenberg, Hessen (NEB, N 51.37936 E 9.91365, 247 m ASL)) in two consecutive years (2019–2020 and 2020–2021) to investigate the weed control efficiency of alternative silage maize cropping systems under organic management. The locations have similar soil type (luvisols), but they have different weather patterns with an average annual temperature and cumulative precipitation of 9.1 °C and 690 mm at TRE, as well as 9.3 °C and 638 mm at NEB. For more information, see Schmidt et al. [3].

The experiment followed a row-column design (4 × 20 units with net 30 m<sup>2</sup> plots) with four replications, and included 18 shared treatments tested at both locations, comprising alternative silage maize cropping systems, collected under the terms double cropping system (DCS) and roller-crimper terminated, double cropped, mulched system (DCMS), as well as the sole silage maize cropping system (SCS) as a control to represent common farming practices. Factors ranged from *first crop (group)* (*FC (group)*)—pure winter pea (P) or hairy vetch (V) and their mixtures with a cereal partner (V-Mix, P-Mix), control), *management*—grouping factor comprising *tillage* (RT, NT, Roll and CT), *additional slurry fertilization* (yes-no), *mechanical weed control* (MWC; yes-no) and *row width* (75 cm and 50 cm) in a non-orthogonal and unbalanced manner. Please note that the maize sowing date was adjusted to optimize systems to the number of crops—in SCS, maize was sown earlier than in DCS and DCMS—hence any difference among SCS and DCS, DCMS is also based on the combined effect of the maize sowing date and the presence of winter cover crop. Factors and their combinations are described in Figure 1. For clarity, discussed *factors* are written in italics throughout the paper [3].

The weather conditions varied in the two experimental years: 2019–2020 was relatively dry, especially near the maize sowing and establishment phases. On the other hand, the weather was exceptionally cool and humid for the aforementioned phases in 2020–2021. For more detailed information, see Schmidt et al. [3].



**Figure 1.** Treatment combinations common at both experimental locations. Abbreviations: red. = reduced, till = tillage, add. fert. = additional fertilization.

All plots were prepared with conventional tillage (CT) in autumn (September–November). First crops (FCs) were sown briefly after and were harvested or rolled in early-to-full bloom between the end of May and the beginning of June. Maize was sown shortly after with non-inversion tillage (DCS RT) or no tillage (DCS NT, DCMS) practices. Maize in the control plots (SCS) was sown earlier (beginning of May) after a shallow soil preparation just as for DCS RT. In 2020–2021, there was a ca. 1 month delay of maize sowing in SCS at TRE due to weather circumstances. FC varieties were identical across locations, but maize varieties were adjusted for best results for each location. DCS and SCS were slurry-fertilized in the first four weeks of sowing ( $60\text{--}80\text{ kg N ha}^{-1}$ , location-specific) and hoed on average two times per season (see Schmidt et al. [3] Table A2 for specificities). In the DCS 50 cm treatments at NEB, no MWC could be conducted in 2020–2021. Maize harvesting took place in September–October at BBCH 83–87. In the first experimental year at TRE, a shallow soil disturbance before maize sowing was performed in every DCS plot, and therefore eliminated DCS NT from the experiment (and doubled the representation of DCS RT) [3]. See Schmidt et al. [3] (Appendix A) for more information on the locations, experimental conduct and experimental design.

Weed control efficiency was assessed through the ratio of weed groundcover to maize groundcover development ( $GC_{\text{weed}}$ ) and dominant weed species development (DWS, presence-absence), also grouped by life form ( $DWS_{\text{group}}$ ), related to the groundcover of each species over time. Generally, only one species was selected as DWS (presence), whereas the other species were recorded as absent (not the DWS) for each time-step. The measurements took place on three  $0.5\text{ m} \times 0.5\text{ m}$  permanent quadrats. Quadrats were fully randomized between two rows in the first year (2019–2020), whereas they were always edging a row in the second year (2020–2021). The measurements took place in a two-week rhythm from the silage maize sowing date in the DCS and DCMS systems until canopy closing in the respective plot, giving ca. four repeated measurements in SCS and ca. five in DCS and DCMS (see Table A1 for more information).

This methodology (DWS on a dependent multinomial scale) only assesses the most dominant species per treatment and does not relate 1:1 to the intact weed community. Species may have been consistently present in a treatment, yet never to the extent to be the DWS. Thus, the evaluation has three important limitations: (1) Results are depen-



dent. If a species or group is highly represented, other species or groups will be less represented. Therefore, each group (or species) needs to be seen as a part of the whole community—here, the DWS community. (2) Introduced species (FC) and the natural vegetation were not distinguished from each other for DWS, due to their dependent nature and potential competition with maize. (3) Results only show the DWS community and not the intact/full community structure of the field, as the proportion of DWS and not the proportion of all observed weed species were measured. Nevertheless, this methodology allows a focused comparison of treatments, with only the most thriving species being considered.

Data were organized, graphically presented and statistically analyzed with Microsoft Excel 2016 and R version 4.0.4 [48] through RStudio version 1.4.1106 [49].

Due to subsampling and the time series nature of the data, pre-processing was carried out prior to statistical analysis.  $GC_{weed}$  was averaged over each plot and summarized over time according to the relative area under the disease progress stairs (AUDPS) process [50]. The relative proportion of DWS was calculated within a plot and summarized over time with the relative AUDPS process. DWS values were again adjusted to give a plot sum of 1. The resulting DWS dataset contained nearly 95% zero values in each location; therefore, species were grouped by life form—according to [51]—into four groups ( $DWS_{group}$ ): (1) winter annuals (primary emergence in autumn), (2) summer annuals (primary emergence in spring), (3) winter-summer annuals (similar emergence in autumn and spring) and (4) biannuals-perennials for modelling and statistical analysis. Further information on measuring  $GC_{weed}$  and the data preparation can be found in Appendix B, whereas all species and their respective groups are listed in Table A3.

Based on Schaarschmidt and Vaas [52] and Piepho et al. [53], a generalized linear mixed effect model (GLMM) with a single fixed effect for all 18 treatment combinations (Figure 1) was fitted for both locations separately with a random effect for *year* ( $n = 2$ ). This analysis provided mean estimates for  $GC_{weed}$  and each  $DWS_{group}$  across the two years. The model for  $GC_{weed}$  is:

$$\text{treatment} + \text{year} + (1 | \text{year:treatment}) + (1 | \text{year:row}) + (1 | \text{year:column}) \quad (1)$$

with the notation: fixed + (1 | random). Models were fitted with a beta distribution and cloglog (TRE) or probit (NEB) link. The models of each  $DWS_{group}$  followed a simplified structure:

$$\text{treatment} + \text{year} + \text{year:row} + (1 | \text{year:treatment}) \quad (2)$$

with the notation: fixed + (1 | random). Models fitted a quasibinomial distribution with logit link and binomial variance, allowing up to 981 iterations. More model specifications are listed in Appendix B.

Following Schmidt et al. [3], contrasts were employed to test hypotheses with three foci: (I) DCS and DCMS versus SCS (pseudo-one-factorial), (II) *management* factor (mixtures only) with *FC* or *row width* interactions and (III) *FC* factor (DCMS only) with *row width* interaction. Using these contrasts, main factor effects (*management*, *FC* and *row width*) and factor interactions were assessed graphically. Means were adjusted for unequal sampling when needed (e.g., at TRE). Confidence intervals for means, contrasts and pairwise differences were adjusted to control the family-wise type I error rate at 5% using the multivariate t (mvt) distribution [54]. The graphs presented for focus (I) allow an in-depth exploration of multi-way factorial interactions. Three-way and higher interactions were not considered in detail because they were often inconsistent.

Additionally, to assess *year* and *year:treatment* interaction effects, a model with both *year* and *treatment* as fixed effects was created. The model is

$$\text{treatment} + \text{year} + \text{year:treatment} + (1 | \text{year:row}) + (1 | \text{year:column}) \quad (3)$$

in the case of  $GC_{weed}$  with the following notation: fixed + (1 | random). The year-wise model was fitted with a gamma distribution and inverse link for TRE, whereas it used a beta distribution and logit link for NEB. The corresponding model for individual  $DWS_{group}$  is

$$\text{treatment} + \text{year} + \text{year:treatment} + (1 | \text{year:row}) \quad (4)$$

with the notation: fixed + (1 | random). The model contained a random effect only for NEB, whereas for TRE, this was eliminated due to singularity issues. Hypotheses were tested similarly as mentioned above, including an additional *year* interaction (difference of differences for factor *year*), as described in Schaarschmidt and Vaas [52]. Further assessment of *year:treatment* interactions was conducted by a graphical inspection.

$DWS_{group}$  model estimates were divided by the sum of all groups for each treatment to force the treatment sum to unity. Then, each raw species proportion was averaged over the years (including absences) and adjusted to their respective  $DWS_{group}$  proportion. The resulting DWS proportions were used to identify the species responsible for up to 75% of the total infestation in the individual treatments, excluding likely rare and underrepresented species with possibly strong spatial dependencies. This resulting subset of the data—also with  $DWS_{group}$  information—was used to compare locations and treatments.

A possible relationship between  $GC_{weed}$  and maize DMY was assessed visually using the raw data points. The details for maize dry matter yield (DMY,  $t\ ha^{-1}$ ) quantified from silage-mature biomass samples dried at 105 °C can be found in Schmidt et al. [3].

The most important statistical packages used were: agricolae [55], glmmTMB [56], MASS [57], DHARMA [58], emmeans [59] and RVAideMemoire [60]. Further packages are listed and detailed information on the analyses can be found in Appendix B.

### 3. Results

In the following sections, results are discussed over *location* and *year*, followed by the three foci of the contrasts: (I) alternative systems versus control, (II) *management* factor and (III) *FC* factor.

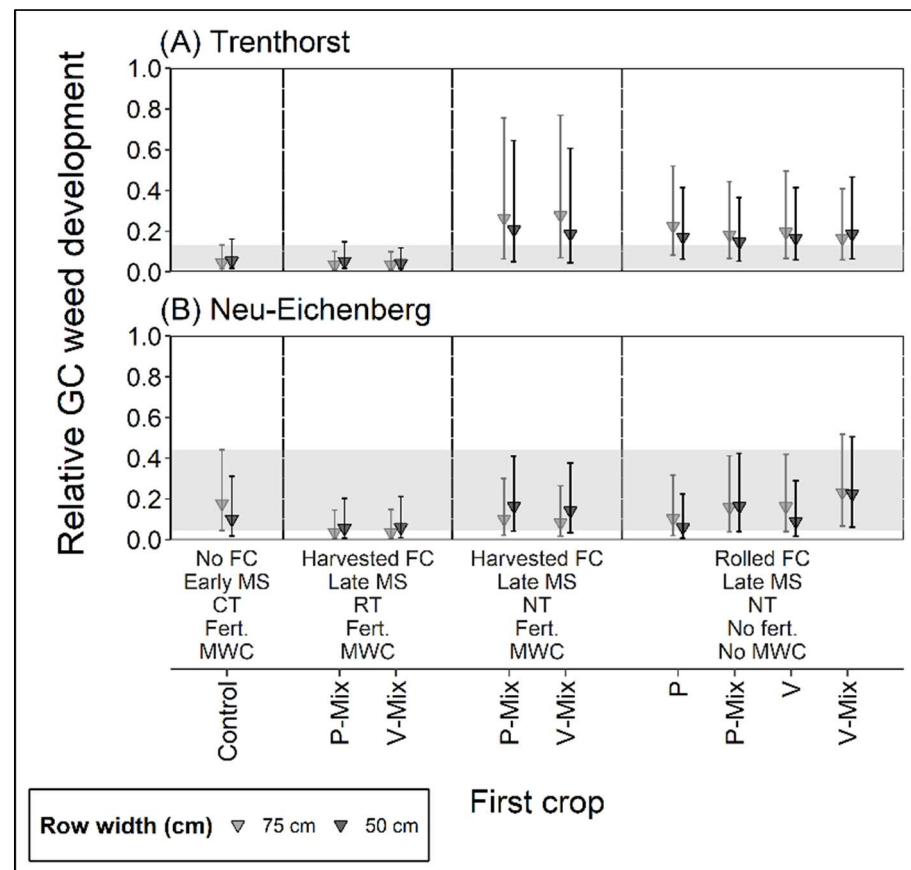
#### 3.1. Relative Weed Groundcover Development

Relative weed groundcover development ( $GC_{weed}$ ) was similar across locations and stayed below 0.28 (e.g., 28%) in all treatments (TRE:  $\bar{x} = 0.15$ ,  $\overline{sd} = 0.08$ ; NEB:  $\bar{x} = 0.12$ ,  $\overline{sd} = 0.06$ ). The overall mean  $GC_{weed}$  difference in the second year compared with the first year was marginal (TRE:  $-0.05$ ; NEB:  $0.07$ ).

Focus I: DCS/DCMS  $GC_{weed}$  compared with SCS were site-specific (significantly) higher (mostly part of TRE), statistically similar (partially TRE and mostly part of NEB) or non-significantly (NS) lower (partially NEB) (Figures 2 and 3 part I). The reduced row width in SCS had no (TRE) or only a marginal effect (NEB). Despite the differences to the 75 cm SCS, factor effects behaved in a similar manner:

Focus II: *Management* was the most influential factor in the model at both locations, where RT significantly reduced  $GC_{weed}$  compared with NT and Roll (Figure 3 part II). NT was similar to Roll. There was no apparent two-way interaction between *management* and *FC* at any location and only a marginal interaction between *management* and *row width* at NEB (RT and NT suppressed slightly more weeds in maize with 75 cm row width).

Focus III: *FC* or *FC group* had little influence on  $GC_{weed}$  at both locations (Figure 3 part III). There was a slight trend at NEB with fewer weeds in Pure and in P(-Mix) versus V(-Mix). *Row width* had no (TRE) or marginal influence—only in DCMS Pure (NEB).



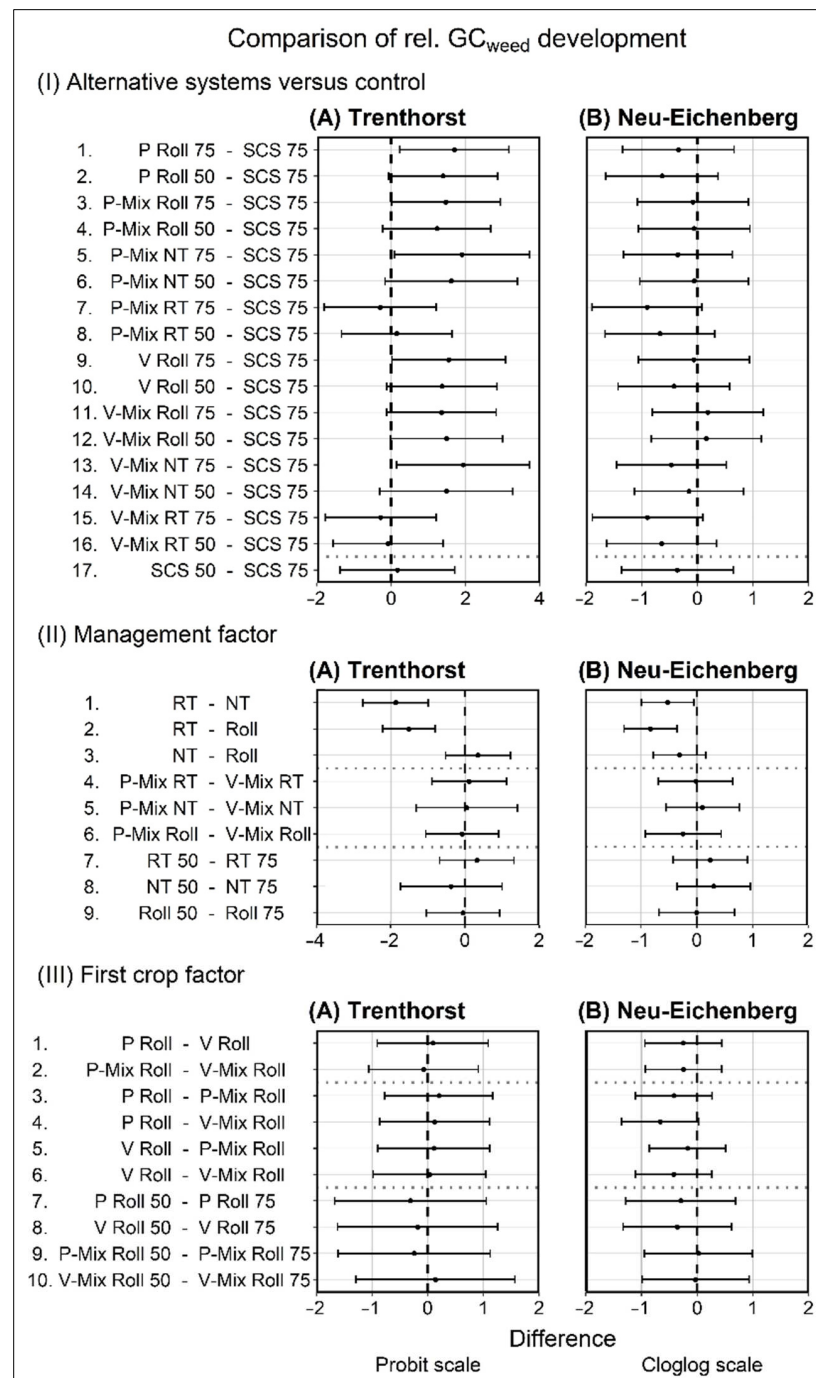
**Figure 2.** Relative weed groundcover ( $GC_{weed}$ ) development over the season averaged over *year* at the two locations. The x-axis shows the *first crop* factor (P = winter pea, V = hairy vetch, P-Mix = winter pea and cereal mixture, V-Mix = hairy vetch and cereal mixture) grouped by *management* (FC = first crop, MS = maize sowing, CT = conventional tillage, RT = reduced tillage, NT = no tillage, Fert. = fertilization, MWC = mechanical weed control). *Row width* is indicated by colours. Error bars represent the 95% CI of the estimates after multivariate t adjustment. The grey background indicates the 95% CI of the 75 cm SCS for a better comparison. Please note that TRE had DCS NT treatments only in the second year.

### 3.2. Relative Proportion of Dominant Weed Species Groups over the Season

In the following subsections, winter annuals—introduced species (FC)—are evaluated separately, as these species are part of DCS and DCMS. Summer and winter-summer annuals are discussed together, whereas biannuals-perennials are excluded from the comparisons due to low representation in the field, especially at TRE (Table A2). Figure 6 summarizes the results over every  $DWS_{group}$ .  $DWS$  and their respective groups are listed in Table A3, whereas their proportions are shown in Figure A3. After the first mention of the scientific names of individual species, the genus is abbreviated with two letters to exclude confusion among different genera. In species assemblages, the first species listed refers to the most abundant species. For example, in *Veronica* spp. (*Ve. persica* Poir., *Ve. agrestis* L., *Ve. arvensis* L.), it is *Ve. persica*. All other species are listed irrespective of their weight in the total abundance in the respective assemblage.

Measurements only assessed the most important genera per quadrat (one species). Therefore, results do not represent the intact weed community structure (see Section 2 for more detail).





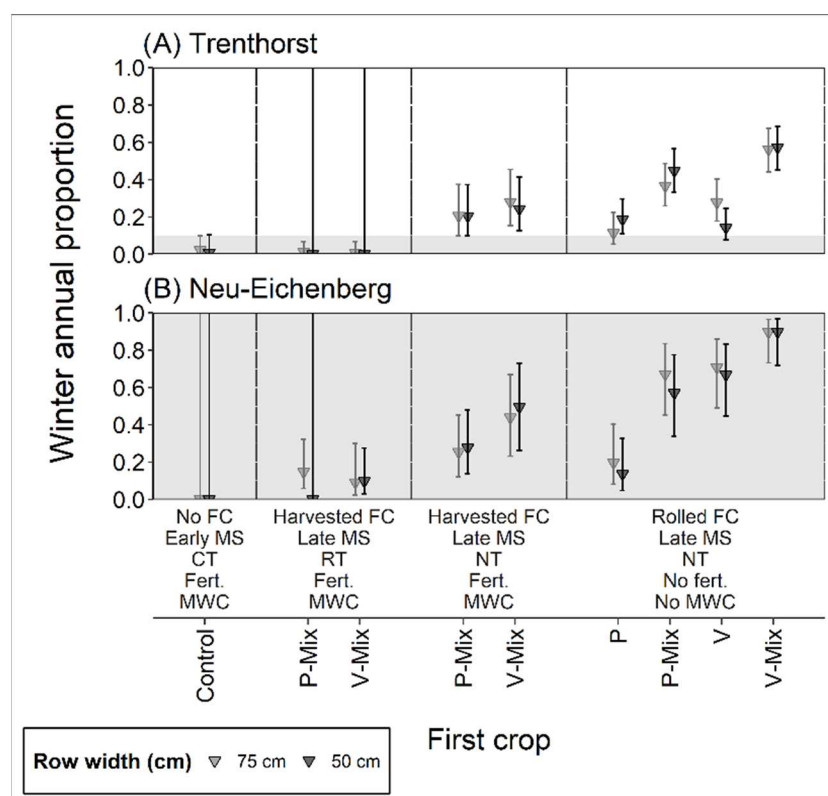
**Figure 3.** Comparison of relative weed groundcover ( $GC_{weed}$ ) averaged over *year* at the two locations with the foci: (I) Alternative systems versus control, (II) Management factor, (III) First crop factor. The contrast in question is shown on the y-axis, whereas its scale is on the x-axis. Factor levels for *first crop* are: P = winter pea, V = hairy vetch, P-Mix and V-Mix = their mixtures with a cereal partner; for *management* are: SCS = control, RT = reduced tillage, NT = no tillage, Roll = rolling of first crop; and for *row width* are: 75 cm and 50 cm. Points represent the linear contrasts of mean estimates as subtraction (on probit or cloglog scale). The vertical dashed lines at 0 show the  $H_0$ , where the difference of estimates is 0 (estimated means are equal). Error bars show the 95% CI of the estimated difference after multivariate t adjustment. Thus, when this crosses the vertical dashed line ( $H_0$ ), there is statistically no or non-significant difference between means at  $\alpha = 0.05$ . Each focus group is analyzed independently. Please note that DCS NT treatments at TRE were only present in the second year.

### 3.2.1. Relative Proportion of Winter Annuals

Winter annuals represented the FC (see Schmidt et al. [3] Table A3 for more information).

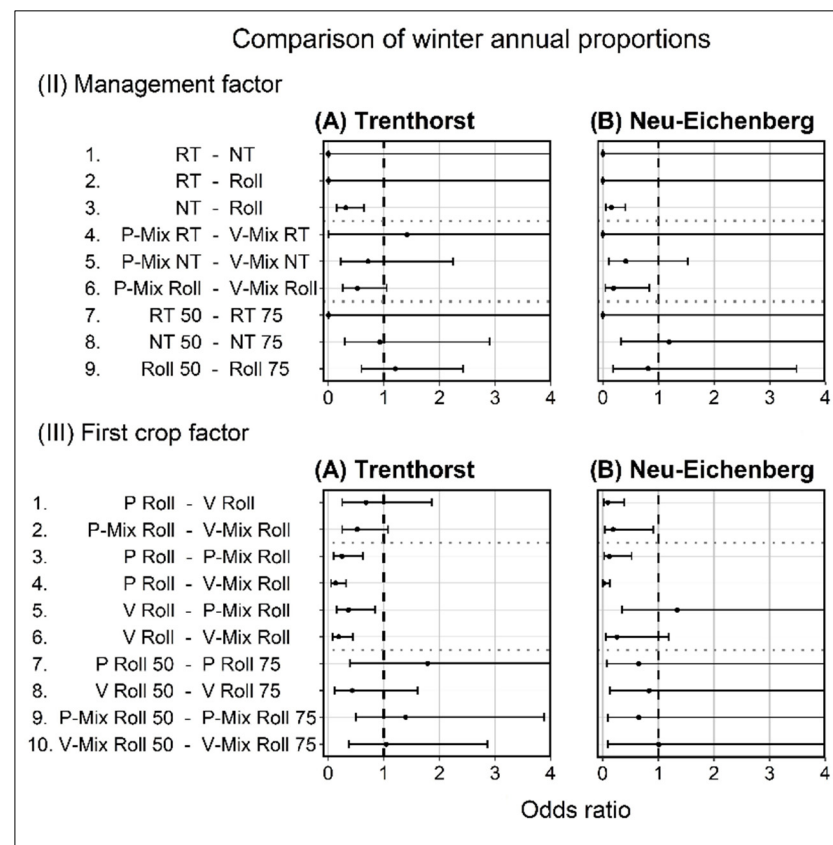
The relative proportion of winter annuals among the dominant weed species (DWS) ranged from 0.00 to 0.57 ( $\bar{x} = 0.20$ ,  $\overline{sd} = 0.19$ ) at TRE and from 0.00 to 0.90 ( $\bar{x} = 0.36$ ,  $sd = 0.31$ ) at NEB. The overall mean proportion at NEB was 180% of that at TRE. A difference in overall mean winter annual proportion compared with the first year was absent at TRE (0.01) and positive at NEB (0.20).

Focus I: DCS/DCMS relative proportion of winter annuals compared with SCS was generally (significantly) higher, except for TRE DCS RT (Figure 4, see Appendix B for reasoning). The reduced row width in SCS naturally had no effect at either location. The factor effects behaved similarly across locations.



**Figure 4.** Winter annual proportions at the two locations averaged over *year*. The x-axis shows the *first crop* factor (P = winter pea, V = hairy vetch, P-Mix = winter pea and cereal mixture, V-Mix = hairy vetch and cereal mixture) grouped by *management* (FC = first crop, MS = maize sowing, CT = conventional tillage, RT = reduced tillage, NT = no tillage, Fert. = fertilization, MWC = mechanical weed control). *Row width* is indicated by colours. Error bars represent the 95% CI of the estimates after multivariate t adjustment. The grey background indicates the 95% CI of the 75 cm SCS for a better comparison. Please note that for treatments with only zero observations, the model estimates the full possible range (0–1) as CI. Additionally, DCS NT treatments at TRE were only in the second year present.

Focus II: *Management* was an influential factor in the model at both locations, in which RT strongly reduced the winter annual proportion compared with NT, which was also significantly more efficient in reducing winter annuals than Roll (Figure 5 part II). NT and RT rather promoted the cereals, whereas Roll favored the viny legumes (Figure A3). The two-way interaction of *management* with *FC* or *row width* was location-specific with similar patterns: For NT and Roll, P-Mix had fewer winter annuals (TRE and NEB). A similar pattern was observed in the RT treatments at NEB, whereas no apparent effect was detectable at TRE. There were only marginal interactions between *management* and *row width*.



**Figure 5.** Comparison of winter annuals averaged over *year* at the two locations with the foci: (II) Management factor, (III) First crop factor. The contrast in question is shown on the y-axis, whereas its scale is on the x-axis. Factor levels for *first crop* are: P = winter pea, V = hairy vetch, P-Mix and V-Mix = their mixtures with a cereal partner; for *management* are: SCS = control, RT = reduced tillage, NT = no tillage, Roll = rolling of first crop; and for *row width* are: 75 cm and 50 cm. Points represent odds ratios for treatment comparisons. The odds ratios were computed using exponential transformation of the linear contrasts of mean estimates on the logit-scale (log-odds scale). The vertical dashed lines at 1 show the  $H_0$ , where the odds ratio of the estimates is 1 (estimated means are equal). Error bars show the 95% CI of the estimated difference after multivariate t adjustment. Thus, when this crosses the vertical dashed line ( $H_0$ ), there is statistically no or non-significant difference between means at  $\alpha = 0.05$ . Each focus group is analyzed independently. Please note that for treatments with only zero observations, the model estimates the full possible range (0–1) as CI. Additionally, DCS NT treatments at TRE were only present in the second year.

Focus III: FC and FC group had substantial effects in DCMS at both locations (Figure 5 part III). Mixtures had higher winter annual species proportions than pure legumes. Furthermore, there was a trend of V(-Mix) being a more problematic FC, especially at NEB (significant differences). All DCMS had a considerable infestation of their respective legume species (Figure A3). Two-way interaction between FC and *row width* was mostly consistent (positive: TRE V, NEB P(-Mix), V; non-existent: V-Mix).

### 3.2.2. Relative Proportion of Summer and Winter-Summer Annuals

The two locations differed in  $DWS_{group}$  representation, but patterns were similar: More winter-summer annuals than summer annuals were present at both locations. There was an additionally large *Lamium purpureum* L. infestation (summer annual) at TRE, especially in the second year. The most important summer annual species were *La. purpureum* L., *Poa annua* L. and *Capsella bursa-pastoris* (L.) Medik. at TRE and *Chenopodium album* L., *Fallopia convolvulus* (L.) Á. Löve, *Persicaria lapathifolia* (L.) Gray and *La. purpureum* at NEB. The most important winter-summer annuals were *Veronica* spp. (*Ve. persica* Poir., *Ve. agrestis* L. and

*Ve. arvensis* L.), *Myosotis arvensis* (L.) Hill., *Matricaria* spp. (*Tripleurospermum inodorum* (L.) Sch. Bip., *Anthemis arvensis* L., *Matricaria chamomilla* L. and *Ma. discoidea* DC.), *Stellaria media* (L.) Vill., *Alopecurus myosuroides* Huds. and *Geranium rotundifolium* L. at TRE, and *My. arvensis*, *St. media*, *Ve. persica*, *Ma. chamomilla*, *Aphanes arvensis* L., *Galium aparine* L. and *Ve. arvensis* at NEB.

The relative proportion of summer annuals among the DWS ranged from 0.03 to 0.75 ( $\bar{x} = 0.21$ ,  $\overline{sd} = 0.20$ ) at TRE and from 0.01 to 0.60 ( $\bar{x} = 0.20$ ,  $\overline{sd} = 0.21$ ) at NEB. The difference in overall mean summer annual proportion compared with the first year was positive at TRE (0.11) and absent at NEB (0.00). The relative proportion of winter-summer annuals among the DWS ranged from 0.10 to 0.61 ( $\bar{x} = 0.37$ ,  $\overline{sd} = 0.12$ ) at TRE and from 0.05 to 0.56 ( $\bar{x} = 0.26$ ,  $\overline{sd} = 0.15$ ) at NEB. The difference in overall mean winter-summer annual proportion compared with the first year was absent at TRE (0.07) and positive at NEB (0.26).

Focus I: Relative proportion of summer annuals in DCS/DCMS was lower compared with SCS, except for DCS RT at NEB (Figure A1 part I), whereas winter-summer annual proportions were slightly lower (NEB) or similar (TRE) to that of SCS (Figure A2 part I). Exceptions were DCS NT P-Mix (TRE only with 50 cm row width) with higher winter-summer annual proportions, DCS RT at NEB and DCMS V-Mix with lower proportions than SCS (TRE and NEB). Both locations had similar summer annuals in SCS and DCS RT—TRE: *La. purpureum*; NEB: *Ch. album*, *Fa. convolvulus* (Figure A3). Additionally, *La. purpureum* was present in DCMS at TRE. However, these species were not important in DCS NT at either location. Winter-summer annual species were only consistently similar to SCS in DCS RT at TRE (*Veronica* spp.). Row width in SCS had only marginal effects on both  $DWS_{group}$  and no detected effect on the species.

Focus II: Management was an influential factor for both summer annuals and winter-summer annuals at NEB, whereas at TRE, effects were more marginal with one distinct treatment (Figure A1 part II and Figure A2 part II). The resulting patterns were complementary over the two proportions—when one was higher, the other one would be lower—except in Roll V-Mix. Two-way interaction between management and FC was rather present for NT and Roll in winter-summer annuals for both locations, whereas no such interaction was detectable for summer annuals. Management:row width interaction had mostly marginal and inconsistent effects across locations. Summer annual species were present and shared between RT and Roll at TRE (*La. purpureum*), whereas at NEB, only RT showed a consistent presence of summer annuals (*Fa. convolvulus*, *Ch. Album* and *Pe. lapathifolia*), distinguishing itself from NT and Roll (Figure A3). Winter-summer annual species were different at both locations: at TRE, NT promoted *My. arvensis*, RT *Veronica* spp. and *St. media*, whereas Roll was associated with *Matricaria* spp. and *My. arvensis* (Figure A3). A slight pattern of DWS in management over different FC was present: *Matricaria* spp. and *My. arvensis* were more common in NT P-Mix and Roll P-Mix, whereas *Veronica* spp. were more frequently found in NT V-Mix and RT V-Mix. At NEB, NT also promoted *My. arvensis*, whereas RT promoted no winter-summer annual species. Roll had a strong interaction with FC: Roll V-Mix—just like in RT—did not promote winter-summer annuals, whereas Roll P-Mix promoted *Ga. aparine* and *St. media*. Additionally, *St. media* was the shared species for P-Mix over NT and Roll at NEB.

Focus III: The FC effect was relevant at both locations but to a different extent in different  $DWS_{group}$  (Figure A1 part III and Figure A2 part III). At TRE, summer annuals in pure legumes and in V(-Mix) had higher proportions than in mixtures or in P(-Mix). At NEB, pure legumes had a similar pattern of more summer annual infestation, but P had higher proportions than V or any mixture at this location. A consistent interaction between FC and row width was only present at TRE and over pure legumes at NEB. FC patterns in the winter annuals were also more consistent in magnitude: all treatments except V-Mix were similarly highly infested, whereas V-Mix had a low infestation. There were consistently no FC:row width interactions for P. However, a consistent reduction with 50 cm row width for all other treatments was found at TRE. Summer annuals species were similar at TRE (*La. purpureum*) but not at NEB, where a separation over FC group occurred:

only pure legumes facilitated summer annuals, yet the species themselves were inconsistent (Figure A3)—except for *Ch. album* in P. From the winter-summer annuals, *My. arvensis* and *Matricaria* spp. were promoted by P-Mix, whereas *Poaceae*—*Al. myosuroides*, the summer annual *Po. annua* and the perennial *Lolium perenne* L.—were favored by pure legumes. At NEB, *St. media* seemed to be more promoted in P(-Mix), and additionally, *Ga. aparine* was more present in P-Mix than any other FC.

### 3.3. Relationship between Weed Groundcover and Maize Dry Matter Yield

Relative  $GC_{weed}$  over the season and maize dry matter yield had no detectable relationship with *management*, although an apparent negative relationship with some levels of FC—P, partially V and V-Mix—was present (Figure A4).

## 4. Discussion

Results varied across years and distinct locations for all measured parameters. Nonetheless, responses to *management*, partly to FC and *row width* were similar across locations, with an occasionally strong influence of *year*, as the two years under inspection differed throughout the maize cropping season. Consequently, *year:treatment*, *year:location* and *year:location:treatment* interactions regarding total weed presence and species composition were relevant for the measured parameters [39,40]. Differences may depend on the longer-term field history, relative quadrat location (relevant for 75 cm row width) and weather. Substantial weather differences were observed near maize sowing: 2020 was drier, whereas 2021 was cooler and rainier at both locations [3]. These differences influenced sowing dates and further possibilities of MWC (Schmidt et al. [3] Table A2), which likely affected weed presence and species composition. This resulted in no MWC at NEB for DCS in 50 cm row width in 2021. Furthermore, at TRE during 2020, no DCS NT treatment was present.

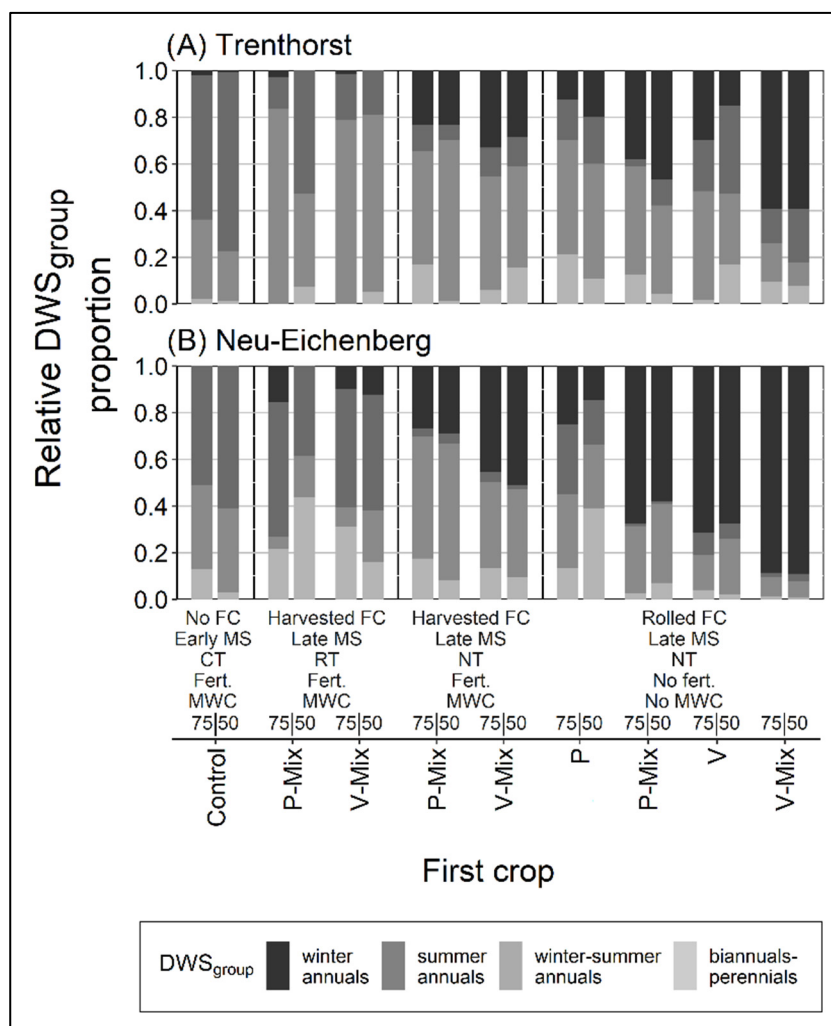
### 4.1. Relative Weed Groundcover Development

Weed groundcover ( $GC_{weed}$ ) was low in all treatments over the two years and locations (estimates always below 0.28), with a relevant *year* effect only at NEB (highest estimate 52% higher in the second year compared with the first year). Treatments—maize and weed emergence, as well as development in general—were strongly influenced by spring soil conditions (e.g., water, temperature and mineralization-complex) [17,19,26,34,61–65]. See Schmidt et al. [3] for a more detailed explanation of these effects of the treatments at hand. These conditions relate to the *system* and *management* factors (SCS CT, DCS NT, DCS RT and DCS Roll). The patterns of  $GC_{weed}$  in these factor combinations were similar at both locations and years ( $DCS RT \leq SCS CT \leq DCS NT \leq DCMS Roll$ ) and were analogous to the effects observed in maize dry matter yield (DMY) of the same experiment [3], even if no apparent correlation of the two variables was present (Figure A4).

Both FC and *row width* had comparatively lower effects than *system:management*, but with mostly consistent directions over *year* and *location*: FC only influenced  $GC_{weed}$  at NEB, where FC regrowth was a serious problem (Figure 6), especially in mixtures and V. This coincided with the higher FC DMY at this location [3], which could have contributed to inadequate control of the FC with the roller-crimper. Furthermore, the early-to-full bloom stage of *Vi. villosa* may have been too early for a successful control of the species, corroborating the findings of Mischler et al. [33] but not by Parr et al. [22]. Thus, these treatments rather introduced weeds (FC) in the rotation. Consequently, the mulch effect on only the native weed infestation ( $GC_{weed}$ ) cannot be evaluated in this experiment. Therefore, the differences between DCMS Pure and Mix regarding the physical boundaries posed on maize development [3] cannot be confirmed for weed development. The *row width* effect was consistent at each location over the two years, but they were—except for DCMS Pure—location-specific. Some artefacts near detection/model boundaries may be created (for TRE SCS CT, DCS RT and NEB DCS RT). Nevertheless, every SCS and DCS at NEB—in contrast to DCMS Pure—consistently showed higher weed infestations in reduced row width, while *year* influenced only the magnitude, due to the generally higher weed infesta-



tion in year 2020–2021, which was attributed to wet weather circumstances and resulted in suboptimal conditions for crop management. Results contradict previous findings [16,25], where a narrower *row width* reduced weed infestations. However, in this experiment, relative to row width, only two-thirds (75 cm) or the whole width (50 cm) between rows were sampled, which may have distorted results due to unequal representation of between-row space. Furthermore, the methodology differed between years, so results related to *row width* must be treated with caution. An additional, system-related error source was the missing MWC at NEB for DCS 50 in the wet and cool 2020–21. Two-way interactions of *management:FC* or *management:row width* were generally marginal.



**Figure 6.** Relative proportion of dominant weed species groups ( $DWS_{group}$ ) at the two locations averaged over *year*. The x-axis shows the *first crop* factor (P = winter pea, V = hairy vetch, P-Mix = winter pea and cereal mixture, V-Mix = hairy vetch and cereal mixture) grouped by *management* (FC = first crop, MS = maize sowing, CT = conventional tillage, RT = reduced tillage, NT = no tillage, Fert. = fertilization, MWC = mechanical weed control) and *row width* (75 cm and 50 cm). Colours indicate  $DWS_{group}$ . Proportions were related to total DWS based on estimates. Additionally, DCS NT treatments were only present in the second year.

#### 4.2. Relative Proportion of Dominant Weed Species

As mentioned above, *year:location* may have influenced results due to the exact field location and field history, relative location of quadrats to row, as well as weather conditions. Additionally, the chosen methodology only allows a constrained comparison of treatments. The three crucial constraints are: (1) Each DWS and  $DWS_{group}$  is part of the whole. There-

fore, individual results are dependent on the respective community composition; (2) the natural weed community and FC regrowth were evaluated on the same scale (DWS). Due to this, detecting a particular effect on the natural weed flora was limited in some cases. (3) Only the DWS community was evaluated and not the community of all observed weed species present in the fields. Therefore, caution is required when interpreting individual DWS responses to *factor*/factor level.

#### 4.2.1. Relative Proportion of Winter Annuals

Relative proportion of winter annuals was greatly influenced by *system* (DCS and DCMS versus SCS) and further by both *management* and *FC*. Marginal regrowth was observed in RT, whereas NT and especially Roll had substantial FC regrowth. In NT, the problematic FC-component was the cereal partner, which could not be adequately destroyed without a shallow soil tillage. After the first MWC, proportions of FC in the weed flora were substantially reduced. In Roll, the legume partners could survive the rolling with roller-crimper in the mixtures—especially at NEB—possibly related to biomass production, machinery and FC phenology [33] (see Section 4.1). Termination problems prevailed at NEB even after using a Cambridge roller combined with the roller-crimper in 2020–2021. Therefore, a less aggressive, probably earlier maturing hairy vetch (and winter pea) variety, a further reduction or omission of the cereal companion in the mixtures and/or an improved destructive power by the roller-crimper (weight) may increase FC destruction success in DCMS.

#### 4.2.2. Relative Proportion of Summer and Winter-Summer Annuals

Relative proportions of summer and winter-summer annuals were location-specific and highly influenced by *year* (data not shown). Rotations at both locations focused on summer and winter cereals (not maize) and moderately on legumes and grass-clover mixtures. Other crops, such as rapeseed or potato were occasionally present in the past 10 years. Therefore, one would expect a greater proportion of winter-summer annuals than summer annuals in the weed community [39,40,44].

At TRE in 2020–2021, the increase in summer annuals in the second year was probably related to the massive infestation of *La. purpureum* and from *Po. annua*, whereas the slight increase in winter-summer annuals could not be attributed to individual species. Summer annuals were also highly influenced by *year* at NEB—increased in DCS RT and SCS CT; decreased in DCS NT and DCMS—despite having no difference between grand means. Winter-summer annuals showed a complementary pattern, except in DCS RT and DCMS V-Mix, which both remained less infected by winter-summer annuals.

In the case of summer annuals, *system* (TRE) or *system:management* (NEB) explained most of the variation. The *system*-effect probably goes beyond the maize sowing date, as no differences were observed among early and late sown SCS at TRE (data not shown). Both SCS CT and DCS RT were made up of similar summer annuals, whereas DCS NT and DCMS had only a marginal summer annual presence, which suggests that the similarities in these groups may guide the DWS community for summer annuals. A logical explanation would be that summer annuals—such as *Fa. convolvulus*, *Ch. album*, *Persicaria* spp. and *Ca. bursa-pastoris*—have relatively high temperature requirements for emergence, which could be reached through shallow soil disturbance (seedbed preparation or MWC) [17,61–63], and their predominant emergence time coincides with related management steps in maize production [8,25,26,31,38,40]. This is supported by the fact that these species are rather well represented throughout the maize fields in Germany [41]. On the other hand, *La. purpureum*, as the most problematic species at TRE, could only be successfully reduced by DCS NT, suggesting that other mechanisms are also involved in the germination of *La. purpureum* which are not connected to soil disturbance or light conditions due to the difference among DCS NT and DCMS (Mix and Pure) [65]. Nevertheless, the *FC* group also had a location-specific strong effect on summer annuals: pure legume mulches facilitated (slightly) more summer annuals than the mixtures. At NEB, the strong overrepresentation of the *Vi. villosa*

probably reduced the magnitude of this effect. This could be related to more differences, e.g., light, temperature and nutrient requirements for emergence and establishment that are hindered to a different extent in DCMS Pure and Mix [18,21,22,28,30,34].

Winter-summer annuals were more location-specific than any other DWS<sub>group</sub>. At TRE, only DCMS V-Mix was different from all other treatments. Nevertheless, a slight variation was still present—following the pattern seen at NEB—which pattern could appear more pronounced with increasing yearly repetitions. At NEB, *management* affected the winter-summer annuals strongly, where especially DCS RT had consistently low infestations. Species followed a similar trend, with *system:management*-specific DWS communities in the group. Only one species assemblage—*Veronica* spp.—at TRE was shared by SCS CT and DCS RT. The apparently missing effect of SCS sowing date stays uncertain due to the steeply increased representation of *Veronica* spp. in year 2020–21, where SCS sowing dates were only one week apart. Nevertheless, similarly as for summer annuals, the common soil disturbance in the early season possibly promoted the emergence [17,61–63]. However, de Mol et al. [39] found that these species—mainly representing *Ve. persica*, such as in this experiment—prefer unploughed fields with high crop densities. Additionally, with the late maize sowing date, *St. media* presence—one of the most common species in maize fields [39,42]—increased in DCS CT, making it similar to DCS RT (data not shown). This species was also more represented in 2020–21. *My. arvensis* was the only species consistently represented at both locations in DCS NT. This species (phenotype) may require light for emergence, as suggested by their lower presence in disturbed or mulched plots. Nevertheless, both locations showed an interaction of *management* and *FC* for this species, suggesting a residue quality-based difference of the legumes. At NEB, winter-summer annuals were not promoted in DCS RT, possibly due to the higher proportion of summer annuals and biannuals-perennials. Despite the low GC<sub>weed</sub> in DCS RT—therefore a generally good weed control—perennial weed species are still present in the DWS flora (Figure 6) and may cause problems throughout the rotation [25,44,66]. Next to *management*, *FC* also had a very strong effect, where V-Mix promoted fewer winter-summer annuals than any other *FC*. This is possibly related to the high presence of *Vi. villosa* (TRE and NEB) and *La. purpureum* (TRE). Furthermore, DCMS Pure promoted more *Poaceae* at TRE, irrespective of their DWS<sub>group</sub>, possibly related to the efficient nutrient scavenging of these species [19,20]. Further patterns of *management:FC*, *FC* or *FC group* were also present (*Matricaria* spp., *My. arvensis*), suggesting similar possibilities as for *My. arvensis* discussed for *management:FC*.

#### 4.3. Relationship between Weed Groundcover and Maize Dry Matter Yield

GC<sub>weed</sub> and maize DMY had no apparent relationship with the *management* factor and only a partial relationship with *FC* (Figure A4). General weed infestation was indeed low relative to maize groundcover, which could result in low interspecies competition [25,67]. The high regrowth of legumes in the DCMS Mix also did not influence maize DMY consistently. However, due to the weather variation and low *year:location* combinations, no clear pattern only shows that in distinct conditions, this method did not find any clear evidence of a relationship between these variables [26]. Even if weed infestation did not influence maize DMY, there could still be a negative effect on the following crops if species can reproduce [25].

## 5. Conclusions

In this study, a wide scope of factor combinations were examined (*FC*, *management* and *row width*) on weed groundcover development (GC<sub>weed</sub>) and short-term dominant weed species group (DWS<sub>group</sub>—winter annuals, summer annuals, winter-summer annuals, biannuals-perennials) shifts, proportional to the community of DWS<sub>group</sub>. Effects on some DWS could also be evaluated with care on representation in the field and year.

A high variation among environments (years and locations) occurred, yet patterns were similar across locations: Number of crops (*system*) and their interaction with *manage-*



**Table A1.** *Cont.*

Location	Year	Distinct Factors	t <sub>0</sub>	t <sub>1</sub>	t <sub>2</sub>	t <sub>3</sub>	t <sub>4</sub>	t <sub>5</sub>	t <sub>6</sub>
NEB	2019–20	SCS	0	36.5	50				
		SCS, row 1	0	13.5	28	41.5	55.5		
		DCS, DCMS	0	13.5	28	41.5	55.5	75.5	
	2020–21	SCS	0	48	63	76.5	90.5		
		DCS 75 cm	0	23	38	51.5	65.5		
		DCMS	0	15	30	43.5	57.5		
		DCS 50 cm	0	10	25	38.5	52.5		

**Appendix B**

Additional information is provided for data pre-processing and analysis. Overlaps with some parts of Section 2 and Schmidt et al. [3] are present to keep explanations cohesive.

Relative weed groundcover ( $GC_{weed}$ ) development was measured from above. Therefore, weeds masked by the maize canopy were not assessed, hence the rationalization to maize groundcover development.

Due to the nature of the data (subsampling and time-series), data were pre-processed prior to statistical analysis. At each date,  $GC_{weed}$  was averaged within a plot, and combined with days after sowing (DAS) information (Table A1)—with a hypothetical zero  $GC_{weed}$  at maize sowing ( $t_0$ )—to calculate the relative  $GC_{weed}$  over the measurement period from maize sowing until canopy closing according to the relative area under the disease progress stairs (AUDPS) process [50]. Relative AUDPS forces the  $GC_{weed}$  values between zero and one, allowing an easier assessment of the results. DWS presence-absence values at each temporal repetition were summarized over the permanent quadrats (count) and divided by the weed presence in the plot (proportion), resulting in a plot sum of one. These proportions were further processed as  $GC_{weed}$  to calculate the relative DWS proportion of each species over time. Resulting DWS proportions were adjusted to sum to unity plot. This DWS dataset contained nearly 95% zero values in each location; therefore, species were grouped by life form—according to [51]—into four groups ( $DWS_{group}$ ) for modeling and statistical analysis: (1) winter annuals (primary emergence in autumn), (2) summer annuals (primary emergence in spring), (3) winter-summer annuals (similar emergence in autumn and spring) and (4) biannuals-perennials. All species and their respective groups are listed in Table A3.

All treatments in the different locations—two (TRE) and eight (NEB) additional treatments—were involved in the analysis to estimate the experimental error structure as accurately as possible. For further information, see Appendix B in Schmidt et al. [3]. This customization did not change the  $GC_{weed}$  model (1) reported in the Materials and Methods section for TRE:

$$treatment + year + (1 | year:treatment) + (1 | year:row) + (1 | year:column) \tag{A1}$$

with the notation: fixed + (1 | random). Models to identify *year* and *year:treatment* interactions differed to equation (1) by treating *year* as a fixed effect. For TRE, the resulting model is:

$$treatment + year + year:treatment + (1 | year:row) + (1 | year:column) \tag{A2}$$

with the notation: fixed + (1 | random).

In the case of NEB, the model structure was adjusted with additional layout elements [3]. The model for  $GC_{weed}$  is therefore:

$$treatment + year + (1 | year:treatment) + (1 | year:row) + (1 | year:column) + (1 | year:row:column) \tag{A3}$$



and with *year* as fixed effect, it is:

$$\text{treatment} + \text{year} + \text{year:treatment} + (1 | \text{year:row}) + (1 | \text{year:column}) + (1 | \text{year:row:column}) \quad (\text{A4})$$

with the notation: fixed + (1 | random). Variance components were estimated by REML.

Models for  $GC_{\text{weed}}$  were based on a beta distribution with cloglog (TRE) and probit (NEB) link. Both models assumed heterogeneity of variance (through the dispformula [56]) with 10 levels at TRE (custom factor which combines variance magnitude of individual treatments and year) and with three levels for NEB (custom factor with the levels: CT\_Roll, NT and RT). The year-wise model for  $GC_{\text{weed}}$  was fitted with gamma distribution with inverse link and five variance levels (custom factor which combines variance magnitude of individual treatments) for TRE, whereas a beta distribution with logit link and six variance levels (*management*) was used for NEB.

Models for each  $DWS_{\text{group}}$  were fitted with scarce proportional data (many zero values). Therefore, each model was fitted with a quasibinomial distribution alongside a logit link and binomial  $\{\mu(1-\mu)\}$  variance structure with up to 981 model iterations. Based on the constraints of the function used (MASS::glmmpQL [57]), the model structure was simplified to exclude redundant information with near zero explained variation. Therefore, the model structure for each  $DWS_{\text{group}}$  with fixed *treatment* and random *year* effect was:

$$\text{treatment} + \text{year} + \text{year:row} + (1 | \text{year:treatment}) \quad (\text{A5})$$

with the following notation: fixed + (1 | random). The year-wise model for each  $DWS_{\text{group}}$  was fitted with

$$\text{treatment} + \text{year} + \text{year:treatment} + (1 | \text{year:row}) \quad (\text{A6})$$

model structure with the following notation: fixed + (1 | random) for NEB. However, for TRE, this model could not be fitted due to the low explained variance of *year:row* and *year:column* layout effects. Therefore, for TRE, the model was as follows:

$$\text{treatment} + \text{year} + \text{year:treatment} \quad (\text{A7})$$

with each effect being treated as fixed.

The boundary values of each  $DWS_{\text{group}}$  are listed in Table A2 alongside the number of model iterations. Models for biannual–perennial species were only used for mean estimation, and therefore, for estimated proportions.

The sum of the estimated means from each  $DWS_{\text{group}}$  could be inspected to check the strength of the model power in general, as they should add up to one. This internal control showed good results at NEB, where only 4 out of 26 treatments were underestimated with below  $\sum 0.90$ . From these, only two treatments are included in this article (DCMS P 50 with  $\sum 0.78$  and DCS RT V-Mix 50 with  $\sum 0.79$ ). At TRE, the underestimation was stronger: only 10 out of 20 treatments had a sum of at least 0.90, whereas 15 had a sum of at least 0.80. Only two of these are not included in the evaluation in this article. The less accurately estimated treatments are all in DCS: DCS NT P-Mix 75 ( $\sum 0.85$ ), DCS NT P-Mix 50 ( $\sum 0.88$ ), DCS NT V-Mix 75 ( $\sum 0.84$ ), DCS NT V-Mix 50 ( $\sum 0.85$ ), DCS RT P-Mix 75 ( $\sum 0.46$ ), DCS P-Mix RT 50 ( $\sum 0.84$ ), DCS RT V-Mix 75 ( $\sum 0.45$ ) and DCS RT V-Mix 50 ( $\sum 0.68$ ).

The analysis of mean estimates and linear contrasts utilized Kenward–Roger ( $GC_{\text{weed}}$ ) or containment ( $DWS_{\text{group}}$ ) approximation for the denominator degrees of freedom and multivariate t (mvt) adjustment for the 95% CI. Means were adjusted for unequal sampling with proportional weights (proportional to the number of observations), when required (e.g., at TRE). The hypotheses tested with contrasts had their focus on the differences among alternative systems and control, as well as on main factor effects (*FC*, *management*) and their interactions with *row width* or *FC*. All foci were analyzed separately. Tests were conducted before back-transformation of means. In the case of complete separation in a  $DWS_{\text{group}}$  (only zero or only one values in a treatment), the quasibinomial likelihood estimates the mean correct (zero or one) but the 95% CI is put to the model boundaries

due to the low replication per treatment for such a distribution. This is why, e.g., Figure 4 shows the full range as CI for SCS 75 at NEB or for DCS RT 50 at TRE, and why the first two contrasts in Figure 5 focus II also show a NS effect for, e.g., contrast 1–2, even though it is obviously a very strong difference between these treatments, when someone inspects the means in Figure 4.

**Table A2.** Proportion of zero and one values of the raw datasets of each dominant weed species group ( $DWS_{\text{group}}$ ) at each location and the iterations of the quasibinomial models. (TRE = Trenthorst, NEB = Neu-Eichenberg).

Location	$DWS_{\text{group}}$	Proportion of Zero Values (%)	Proportion of One Values (%)	Model Iterations
TRE	winter annuals	50	0	980
	summer annuals	38	7	4
	winter-summer annuals	31	4	4
	biannuals-perennials	70	0	980
NEB	winter annuals	45	7	981
	summer annuals	46	5	3
	winter-summer annuals	42	3	981
	biannuals-perennials	58	1	895

Factor effects (*management*, *FC* and *row width*) and their interactions were evaluated through the graphical inspection of the linear contrasts. For example, the effect of *management* on  $GC_{\text{weed}}$  response can be assessed by combining the results in Figure 3 focus II contrasts 1–3. Additionally, the *management:FC* interaction can be summarized through the inspection of contrasts 4–6 of the same figure section. In the latter case, if the contrasts are near the vertical dashed line ( $H_0$ ), *FC* would have negligible effect on *management*. However, if these differences differ, an interaction between the factors is present. The strength of this interaction may be estimated from the unit of the x-axis or from the back-transformed means in the related figure (e.g., Figure 2). Consequently, this method is unsuitable to test the statistical significance of interactions.

In the case of *year* and *year:treatment* interactions, next to the evaluation presented above, an additional statistical testing through the calculation of the difference of differences were employed [52]. For example, testing the *year:management* interaction was carried out among others by inspecting the difference between RT and Roll as influenced by *year* with the equation:

$$[(RT_1 - Roll_1) - (RT_2 - Roll_2)] = [RT_1 - Roll_1 - RT_2 + Roll_2] \quad (A8)$$

where the subscript refers to year. As it is shown by Equation (8), the methodology can test differences statistically, yet it fails to reveal the source of these differences.

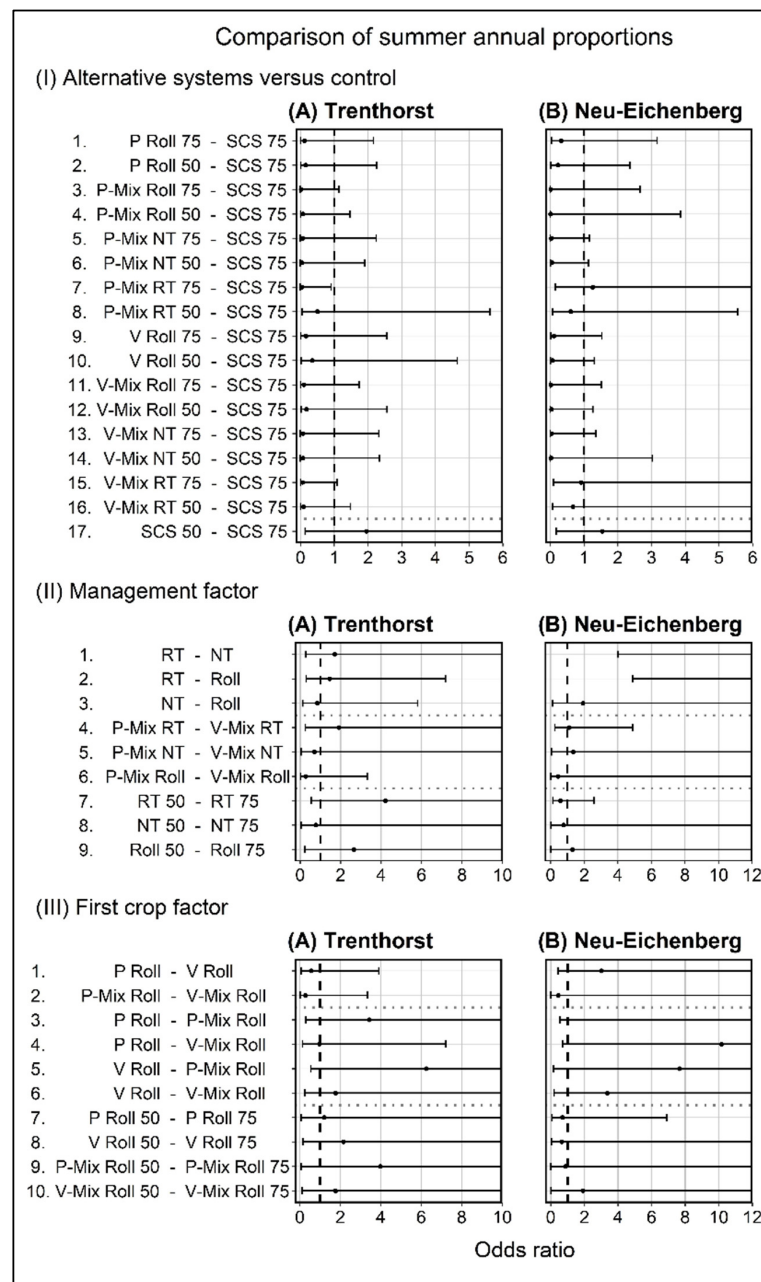
The packages which were used but not mentioned in the Materials and Methods section are readxl [68], dplyr [69], janitor [70], VIM [71], reshape2 [72] and desplot [73] for data preparation and ggplot2 [74], patchwork [75] as well as GGally [76] for data presentation.

## Appendix C

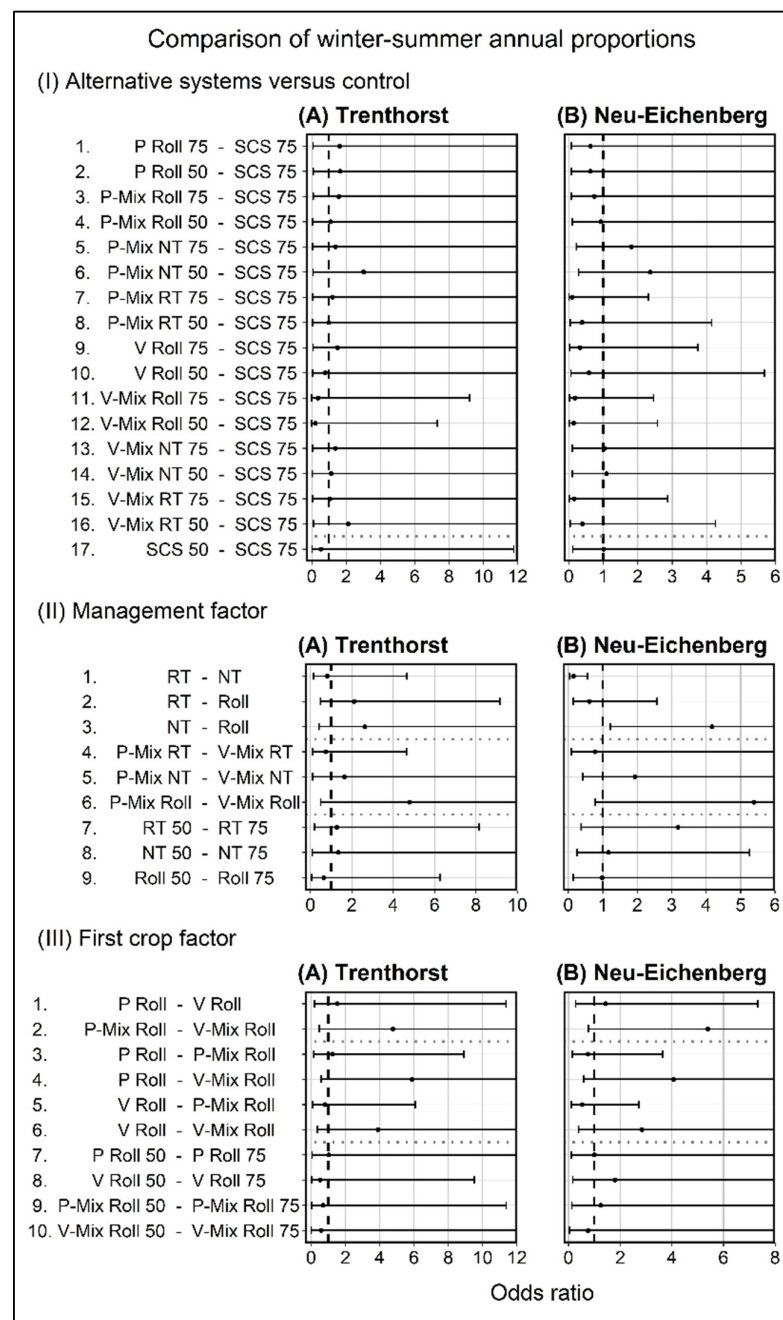
**Table A3.** Average representation of the species (%) on the field averaged over *year* in each DWS<sub>group</sub> at the locations. Sum of total species is put into parentheses and differentiated between more common and seldom (below 1% representation on the field) species. TRE = Trenthorst, NEB = Neu-Eichenberg.

Life form (DWS <sub>group</sub> )	Location (Total Species)	DWS (%)	Percent of Total (%)
winter annuals	TRE (4)	<i>Vicia villosa</i> Roth (10), <i>Pisum sativum</i> L. (6), × <i>Triticosecale</i> Wittm. ex A. Camus (4), <i>Secale cereale</i> L. (3)	23
	NEB (4)	<i>Vi. villosa</i> (16), <i>Pi. sativum</i> (9), <i>Se. cereale</i> (7), × <i>Triticosecale</i> (5)	37
summer annuals	TRE (5 + 2)	<i>Lamium purpureum</i> L. (19), <i>Poa annua</i> <sup>a</sup> L. (2), <i>Chenopodium polyspermum</i> L. (1), <i>Persicaria</i> spp. <sup>b</sup> (1), <i>Capsella bursa-pastoris</i> <sup>c</sup> (L.) Medik. (1), <i>Fallopia convolvulus</i> (L.) Á. Löve (<1), <i>Viola arvensis</i> Murray (<1)	24
	NEB (3 + 4)	<i>Fa. convolvulus</i> (10), <i>Chenopodium album</i> L. (5), <i>Persicaria lapathifolia</i> (L.) Gray (4), <i>Pe. maculosa</i> Gray (<1), <i>Ca. bursa-pastoris</i> <sup>c</sup> (<1), <i>La. purpureum</i> (<1), <i>Vi. arvensis</i> (<1)	19
winter-summer annuals	TRE (6 + 2)	<i>Veronica</i> spp. <sup>d</sup> (10), <i>Matricaria</i> spp. <sup>e</sup> (10), <i>Myosotis arvensis</i> <sup>f</sup> (L.) Hill (8), <i>Stellaria media</i> (L.) Vill. (7), <i>Alopecurus myosuroides</i> Huds. (5), <i>Galium aparine</i> L. (1), <i>Geranium rotundifolium</i> L. (<1), <i>Thlaspi arvense</i> L. (<1)	41
	NEB (9 + 4)	<i>My. Arvensis</i> <sup>f</sup> (10), <i>St. media</i> (5), <i>Aphanes arvensis</i> L. (3), <i>Ga. aparine</i> (3), <i>Matricaria chamomilla</i> L. (2), <i>Veronica persica</i> Poir. (2), <i>Ve. arvensis</i> L. (1), <i>Tripleurospermum inodorum</i> (L.) Sch. Bip. (1), <i>Th. arvense</i> (1), <i>Sonchus asper</i> (L.) Hill (<1), <i>Senecio vulgaris</i> L. (<1), <i>Lamium amplexicaule</i> L. (<1), <i>So. oleraceus</i> L. (<1)	28
biannuals-perennials	TRE (4 + 4)	<i>Lolium perenne</i> L. (6), <i>Equisetum arvense</i> L. (1), <i>Trifolium</i> spp. <sup>g</sup> (1), <i>Cirsium arvense</i> (L.) Scop. (1), <i>Rumex</i> spp. (<1), <i>Quercus</i> spp. (<1), <i>Cichorium intybus</i> L. (<1), <i>Taraxacum officinale</i> F.H. Wigg. (<1)	9
	NEB (3 + 6)	<i>Ci. arvense</i> (8), <i>Medicago sativa</i> <sup>h</sup> L. (2), <i>Rumex crispus</i> L. (2), <i>Solanum tuberosum</i> L. (<1), <i>Trifolium</i> spp. (<1), <i>Lolium multiflorum</i> <sup>i</sup> Lam. (<1), <i>Ru. obtusifolius</i> L. (<1), <i>Silene latifolia</i> Poir. (<1), <i>Ta. officinale</i> (<1)	12

<sup>a</sup> *Poa annua* is either summer annual or perennial (with a life span of only a few years). <sup>b</sup> *Persicaria* spp. are mainly *Pe. maculosa* and less abundantly *Polygonum aviculare* L. <sup>c</sup> *Capsella bursa-pastoris* is either summer annual or biannual. <sup>d</sup> *Veronica* spp. contains mainly *Ve. persica* and, less abundantly, *Ve. agretis* L. and *Ve. arvensis*. <sup>e</sup> *Matricaria* spp. contains mainly *Tr. inodorum* and, less abundantly, *Ma. chamomilla*, *Ma. discoidea* DC. and *Anthemis arvensis* L. <sup>f</sup> *Myosotis arvensis* is either summer annual, biannual or winter annual. <sup>g</sup> *Trifolium* spp. at TRE mainly contained *Tr. repens* L. <sup>h</sup> *Medicago sativa* is either winter-summer annual or perennial. It is under the name *Me. x varia* Martyn (pro. sp.) in [51]. <sup>i</sup> *Lolium multiflorum* is winter annual, biannual or hapaxanth.



**Figure A1.** Comparison of summer annuals averaged over *year* at the two locations with the focus: **(I)** Alternative systems versus control, **(II)** Management factor, **(III)** First crop factor. The contrast in question is shown on the y-axis, whereas its scale is on the x-axis. Factor levels for *first crop* are: P = winter pea, V = hairy vetch, P-Mix and V-Mix = their mixtures with a cereal partner; for *management* are: SCS = control, RT = reduced tillage, NT = no tillage, Roll = rolling of first crop; and for *row width* are: 75 cm and 50 cm. Points represent odds ratios for treatment comparisons. The odds ratios were computed using exponential transformation of the linear contrasts of mean estimates on the logit-scale (log-odds scale). The vertical dashed lines at 1 show the  $H_0$ , where the odds ratio of the estimates is 1 (estimated means are equal). Error bars show the 95% CI of the estimated difference after a multivariate t adjustment. Thus, when this crosses the vertical dashed line ( $H_0$ ), there is statistically no or a non-significant difference between means at  $\alpha = 0.05$ . Each focus group is analyzed independently. Please note that DCS NT treatments at TRE were only present in the second year. The odds ratio for NEB in focus (II) contrast 1 is 24.94, whereas for contrast 2, it is 48.11. The odds ratio for NEB in focus (III) contrast three is 23.18. These were cut off from the plots, so the  $H_0$  line and the nearby points stay less distorted.



**Figure A2.** Comparison of winter-summer annuals averaged over *year* at the two locations with the foci: (I) Alternative systems versus control, (II) Management factor and (III) First crop factor. The contrast in question is shown on the y-axis, whereas its scale is on the x-axis. Factor levels for *first crop* are: P = winter pea, V = hairy vetch, P-Mix and V-Mix = their mixtures with a cereal partner; for *management* are: SCS = control, RT = reduced tillage, NT = no tillage and Roll = rolling of first crop; and for *row width* are: 75 cm and 50 cm. Points represent odds ratios for treatment comparisons. The odds ratios were computed using exponential transformation of the linear contrasts of mean estimates on the logit-scale (log-odds scale). The vertical dashed lines at 1 show the  $H_0$ , where the odds ratio of the estimates is 1 (estimated means are equal). Error bars show the 95% CI of the estimated difference after a multivariate t adjustment. Thus, when this crosses the vertical dashed line ( $H_0$ ), there is statistically no or a non-significant difference between means at  $\alpha = 0.05$ . Each focus group is analyzed independently. Please note that DCS NT treatments at TRE were only present in the second year and that focus (I) were cut in scale for less distortion of the hypothesis testing through inspecting odds ratios compared with the  $H_0$  line.



Appendix D

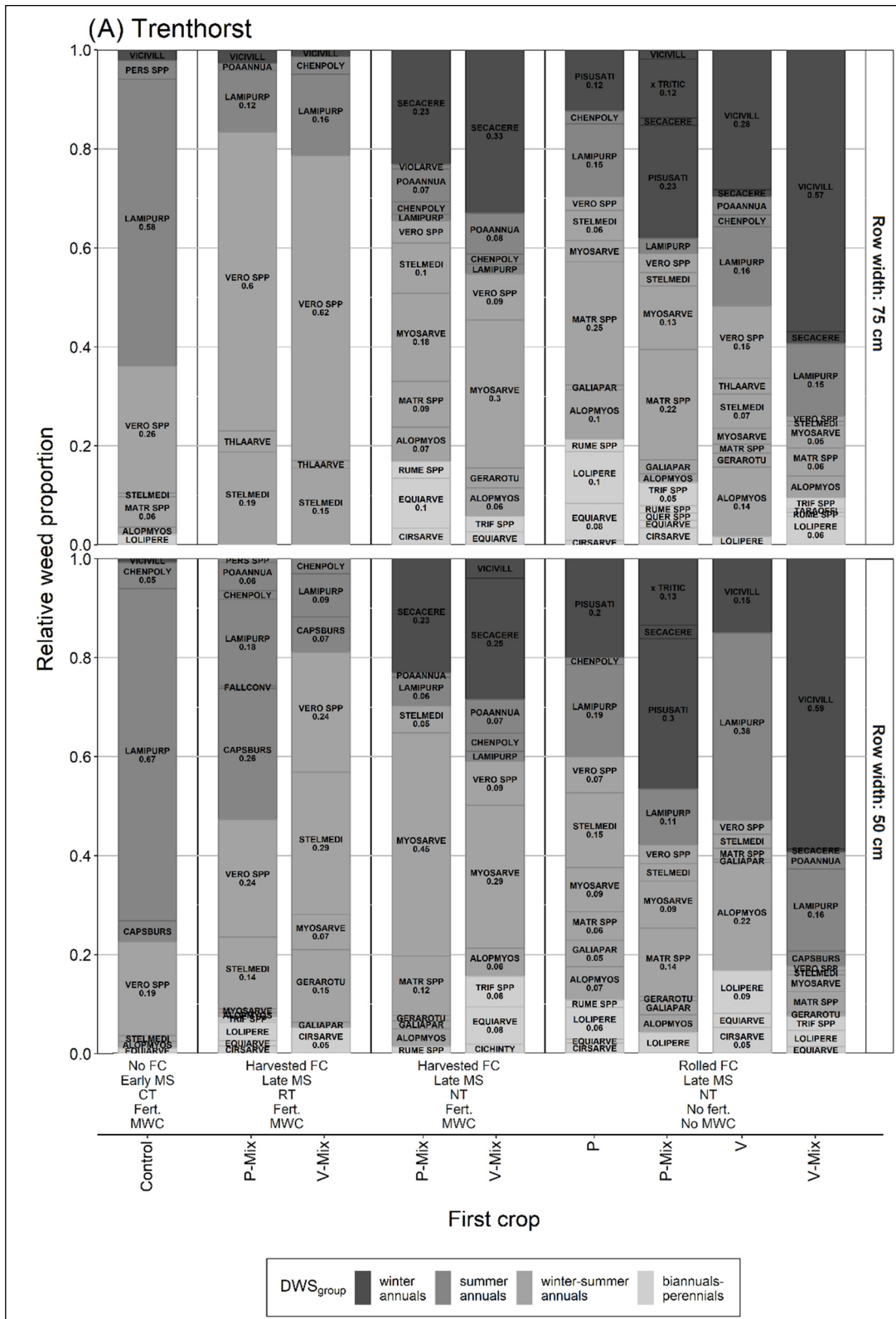
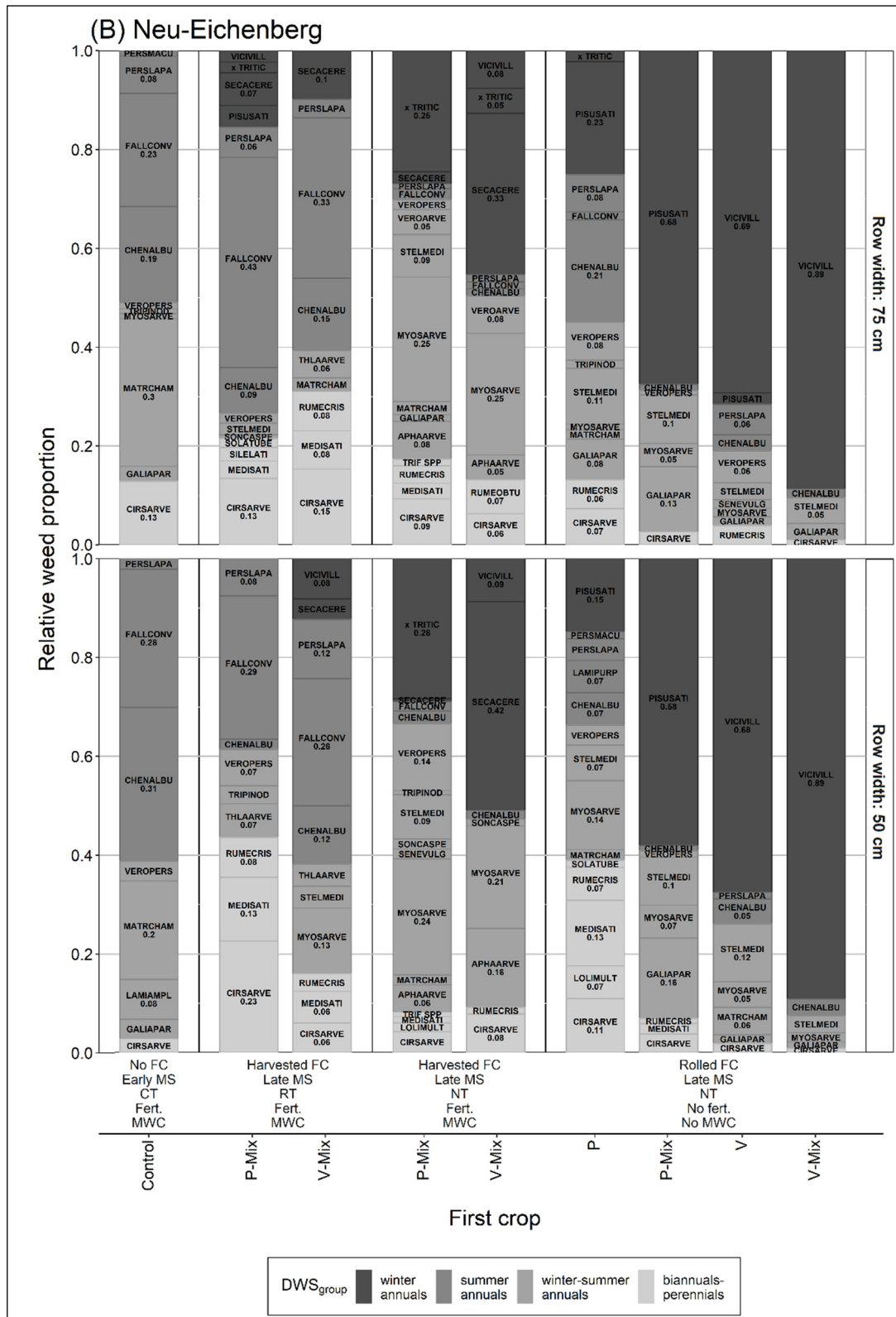


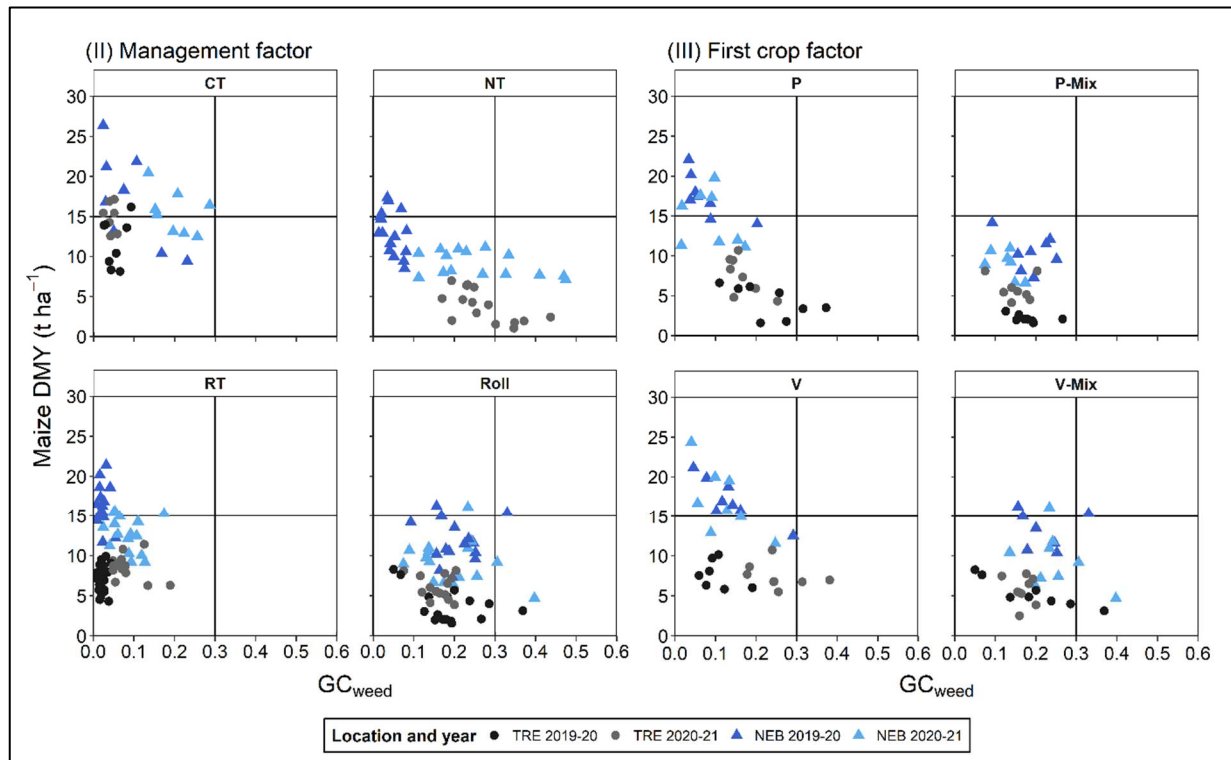
Figure A3. Cont.



**Figure A3.** Relative proportion of dominant weed species (DWS) at (A) Trenthorst and (B) at Neu-Eichenberg averaged over *year*. The x-axis shows the *first crop* factor (P = winter pea, V = hairy vetch, P-Mix = winter pea and cereal mixture, V-Mix = hairy vetch and cereal mixture) grouped horizontally by *management* (FC = first crop, MS = maize sowing, CT = conventional tillage, RT = reduced tillage, NT = no tillage, Fert. = fertilization, MWC = mechanical weed control) and vertically by *row width*

(75 cm and 50 cm). Colours indicate  $DWS_{group}$ . Proportions were related to total DWS based on estimates. Additionally, DCS NT treatments at TRE were only present in the second year. Species are indicated with 4 letters from genus and 4 letters from species (e.g., VICIVILL = *Vicia villosa*).

## Appendix E



**Figure A4.** Relationship between weed groundcover ( $GC_{weed}$ ) and maize dry matter yield (DMY,  $t\ ha^{-1}$ ) over year and location with a focus on (II) Management factor and (III) First crop factor. Shape and colour represent location (shape and colour) and year (depth of colour). CT was included in focus (II) for completeness of important factors.

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