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Management Effects on the Performance of Double Cropping Systems—Results from a Multi-Site Experiment

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Abstract: Traditional (silage) maize production often has negative side-effects related to unprotected soil surface. There are several possibilities to enhance system sustainability through reducing soil disturbance. However, implementation may be hindered due to reduced nitrogen availability and increased weed infestation, especially in organic agriculture. A field experiment to evaluate yield potential of 18 silage maize cropping systems under organic management was conducted at three distinct locations. Examined parameters were first crop, maize and total harvested dry matter yield (DMY), and maize dry matter content (DMC). Treatment factors included *first crop* (*FC*—winter pea, hairy vetch, and their mixtures with rye, control (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 terminated with roller-crimper (DCMS Roll), SCS control), *fertilization*, *mechanical weed control*—and *row width* (75 cm, 50 cm). A high variation among environments occurred, but similar patterns manifested across locations: Number of crops in the rotation had a high influence, followed by *management* and *FC*. *Row width* had only marginal and inconsistent effect. FC mixtures generally yielded higher than pure legumes. Maize DMY in DCS, DCMS was lower than or comparable to SCS. Maize DMC were environment-specifically below acceptable range, especially under DCMS. Total harvested DMY in DCS were similar to or greater than SCS. Results suggest differences from the optimization of farming operations for one (SCS) or two crops (DCS, DCMS) with strong effects at early maize development and on the length of season. *FC use* and *tillage* factors possibly altered the soil water, temperature, and mineralization dynamics, resulting in modified maize growth. DCS RT and DCMS Pure performed with the best maize yields, improved soil protection, and tillage reduction in the silage maize part of the rotation under organic management. However, alternative management systems, especially under DCS NT and DCMS (Mix) with studied maize maturity classes are less suited, particularly in cool and wet spring conditions, because of a potentially slower development of FC, a later establishment of maize plants and therefore, a shorter growing season for the maize crop.

Keywords: silage maize; organic agriculture; winter cover crop; double cropping system; roller-crimper; tillage; row width

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1. Introduction

Silage maize production is on a continuously high level in Germany with nearly 2/3 of this dedicated to fodder use and around 1/3 to biogas production [1,2]. However, associated negative side-effects—e.g., soil erosion and compaction, high weed infestation and intensified weed control [3–5]—of traditional maize production are raising concerns about the sustainability of the system.

Traditionally, under organic management in temperate European conditions, maize —as a row crop—is usually sown into autumn-ploughed soil (CT) in early May with wide, usually 75 cm row width after a long winter fallow. The crop has a high temperature and nitrogen (N) demand, slow juvenile development and therefore, a low competitive ability in the early season. Consequently, most negative effects arise from the open soil surface from the winter until canopy closing of the crop (late June–July). The open soil surface has an increased soil erosion risk, and it offers an open niche to weeds [3,5–7]. This necessitates an intensive mechanical weed control during these early development phases [3,7]. The repeated soil disturbance and the aim to keep the soil surface open enhance the soil erosion risk and promote soil compaction [7,8]. Next to the innate difficulties of the traditional maize production system, an increased variability in local climates and more intense rains as a result of climate change may exacerbate the aforementioned problems [9–13]. These innate difficulties are more pronounced in organic farming as tillage and mechanical weed control—also connected to the nutrient management—are crucial for organic (silage) maize production, remaining without relevant alternatives in Europe. There is a considerable demand to reduce the tillage-based management in organic systems, at least in some phases of the crop rotation [3,7]. As traditional management of row crops involves intensified soil disturbance, reduction of tillage practices at this phase of the rotation may ecologically benefit the whole farming system [8].

Over the decades, several alternative cultivation systems have emerged with the aim to reduce the negative side-effects related to the open soil surface before and in the juvenile development stage of maize and the confounded intensive soil disturbance to control emerging weeds. Some of these alternative systems reduce the traditionally wide row width to push the canopy closing of the crop to an earlier date [5]. Others introduce more complex systems, where a winter cover crop is incorporated into the rotation before maize sowing [3,4]. This winter cover crop protects the soil from erosion and weed infestation over the winter months and reduce nutrient losses [6,7]. It may be harvested (classical double cropping systems (DCS)), or it may be used as an enhancer for the following maize crop (double cropped, mulched system–DCMS).

Winter cover crops may vary according to desired utility, but they should be winter hardy with good establishment and groundcover, have a high potential biomass production combined with early maturity for optimized biomass yield until crop termination in its mid generative phase [3,14–17].

In a classical DCS, the winter cover crop is harvested for fodder or biogas production and therefore, divides production risks among two crops in the season [1]. Consequently, biomass yield and quality are of utmost importance next to the mentioned positive effects over winter and early spring. Cereals—as grass species—are excellent residual N and nutrient scavengers [14,18] with considerable biomass production [1,19], which provide excellent soil cover over the winter. By contrast, legume species produce less biomass [15,19], but the associated *Rhizobia* strains may fix atmospheric N_2 under scarce residual N conditions [14,16,18]. Therefore, the combination of N scavenging cereals with the N_2 fixating legumes offers various benefits. These go beyond the N dynamics [14,20]: The complementary habitus of suitable, viney legumes and cereals support legume growth in the mixture [19] and offers a potentially healthier canopy through better aeration [15]. Additionally, the mixtures offer high yields, DMC and a more balanced C/N ratio for fodder use. After cover crop harvest, reduced tillage (RT) or no tillage (NT) practices leave some residues on the soil surface as protection, with different influence on nutrient and weed management [4,7,21,22].

In DCMS systems, the winter cover crop is used to efficiently protect the soil surface not only over winter, but also during at least the early development phase of the following crop. In this sense, high biomass yield, biomass persistence without N immobilization and still optimal N mineralization levels are desired for adequate weed and nutrient management in the following crop [16,23,24]. The characteristics of cereals point to a rather thick and persistent mulch layer with potential problems if termination date is suboptimal (N immobilization or regrowth) [15,17,23,25–27]. On the other hand, legumes offer less but easily decomposable mulch material with good N provision [15,23,25,28], and therefore, a potentially weaker weed suppression [16,23,25]. Optimal termination remains crucial to avoid regrowth and associated negative biotic effects [14,16,29]. A mixture of the crops may provide a thick mulch cover with better decomposition and N provision rates than pure cereals. However, mineralization is highly dependent on soil temperature. Under a mulch layer, cool and wet conditions delay early season N mineralization [16,19,25] and legume-cereal mixtures show more problems than pure legumes [15]. Holderbaum et al. [15] associated this effect with N immobilization, but this may (partially) be due to the lower temperature increase/lower evaporation under a thicker mulch layer [14,30,31]. This is a crucial setback of DCMS in organic management, where one of the biggest challenges is to time the peak of mineralization to the peak of N and other nutrient demands [32–35].

In German environments, where overwintering cover crops are on the field from September–October until May–early June, hairy vetch and leafy, wild type winter pea has great potential [15,23], also due to reaching their biomass and N concentration peaks between early and late May [36]. As a cereal (companion), rye showed promising results [1,23,37] but also potential difficulties—slower decomposition and mineralization, higher C/N ratio, thick biomass layer, which may hinder maize sowing [23,25].

The cited research material included some of these alternative systems. Most of the organically relevant research concluded that weed management still remains the core challenge in organic silage maize production, which may hinder soil conservation practices [3,7]. Researchers have found that the effect of management on crop yield and weed control is strongly dependent on the weather and environmental conditions [1,7,22,23]. Therefore, they pointed out the importance to understand the systems and the interactions at hand. In the UNSIFRAN project, several aspects of tillage-reduced weed management in silage maize are combined for comparison in three distinct locations over two years across Germany as an exact experiment to evaluate management effects and their interactions on maize and weed development, as well as on yield. The aim of the project is to compare alternative silage maize cropping systems with distinct winter cover crops under different management (DCS with RT or NT, DCMS) and/or reduced row width to the traditional, sole silage maize cropping system (SCS).

The article focuses on maize and total harvested dry matter yield (DMY). The objective of the analysis next to understanding main factor effects (*FC, management, row width*) is to evaluate their interactions among themselves and localities to assist the understanding of guiding principles. The following major hypotheses were targeted: Under organic management, (1) maize DMY is similar in some DCS, DCMS to SCS; (2) maize DMY is higher in DCS RT as in DCS NT. (3) Similarly, maize DMY is higher in pure legume DCMS as in DCMS with mixtures; and (4) Maize DMY is increased with reduced row width, irrelevant of other factors. Additionally, (5) Total harvested DMY from two crops (DCS) produces at least similar or higher yields as SCS.

2. Materials and Methods

A field experiment to investigate yield responses of alternative silage maize cropping systems under organic management was conducted in a row-column design (4 × 20 units with 30 m^2 plots) with four replications in two consecutive experimental years (2019–2020 and 2020–2021) at three locations in Germany, ranging from North to South: Trenthorst, Schleswig-Holstein (TRE); Neu-Eichenberg, Hessen (NEB); Puch, Bayern (PUC). The experiment included 18 shared treatments across locations. These comprise alternative silage maize cropping systems, here collected under the terms double cropping system (DCS) and double cropped, mulched system terminated with a roller-crimper (DCMS); and the sole silage maize cropping system (SCS) as control to represent common farming practices. Several factors are included, ranging from *first crop (group)* (*FC (group)*—pure winter pea (P) or hairy vetch (V) and their mixtures with cereal (V-Mix, P-Mix—see Table A3 for cereal species), control), *management*—grouping factor for several nested subfactors encompassing *tillage* (NT, RT, Roll, CT), *additional slurry fertilization* (yes-no), *mechanical weed control* (*MWC*; yes-no)—and *row width* (75 cm, 50 cm) in a non-orthogonal and unbalanced manner. Figure 1 describes the full scope of factors and their combinations. Throughout the paper, discussed *factors* are written in italics for more clarity.

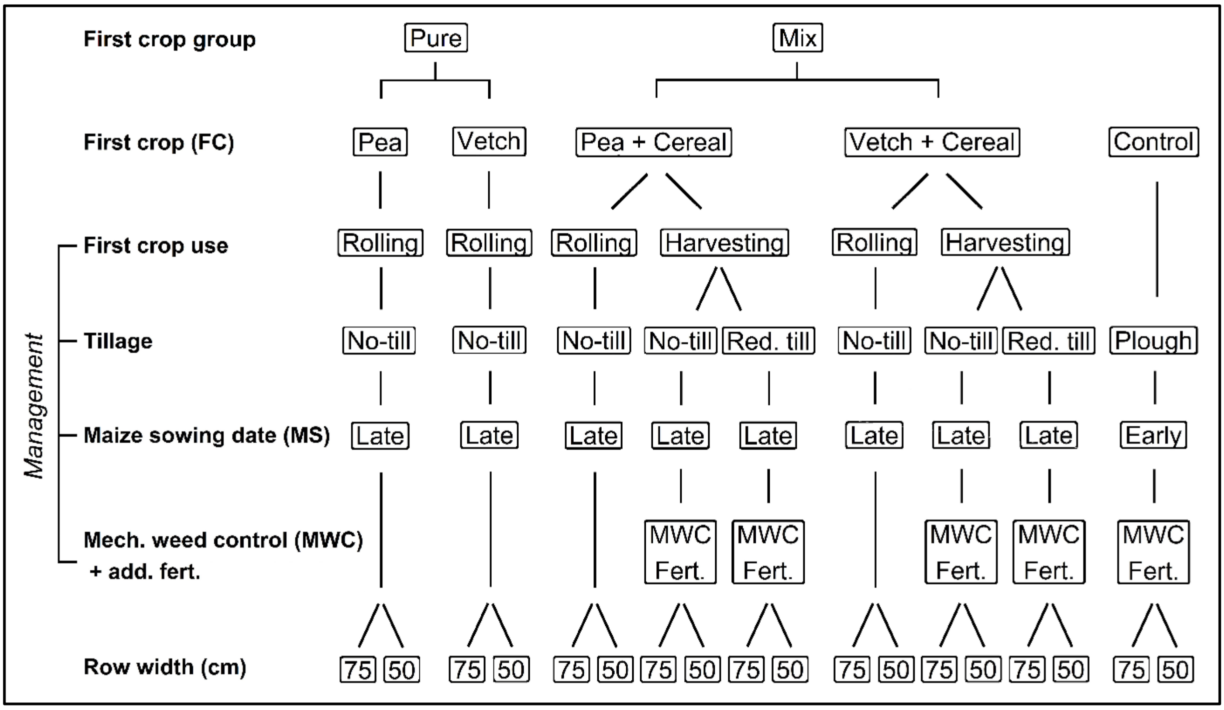

Figure 1. Common treatment combinations at the experimental locations.

Locations have similar main soil types (luvisols)—sandy loams in TRE (pH 6.4, P_2O_5 5.4 mg/100 g, K_2O 12.7 mg/100 g, MgO 9.6 mg/100 g, soil organic matter (SOM) 2.4%) and PUC (pH 6.4, P_2O_5 16 mg/100 g, K_2O 20 mg/100 g, MgO 16 mg/100 g), and silty clayey loam in NEB (pH 6.9, P_2O_5 9.5 mg/100 g, K_2O 11.5 mg/100 g, MgO 14 mg/100 g, SOM 2.4%)—but they differ in elevation (ASL) and weather characteristics. ASL, average temperature and precipitation per year are: TRE: 40 m ASL, 9.1 °C, 690 mm; NEB: 247 m ASL, 9.6 °C, 614 mm; and PUC: 556 m ASL, 8.9 °C, 869 mm.

FCs were sown weather-dependent between mid-September and mid-November after conventional tillage (CT) and harvested or rolled at the end of May until early June in early-to-full bloom development stage of the cover crops. Maize was sown shortly after the harvest/roll of the FC with non-inversion tillage practices in RT, and no tillage practices in NT and Roll treatments. Control maize (SCS) was sown in early May after an autumn CT and non-inversion tillage right before sowing. Sowing of SCS was delayed in 2021 in TRE and PUC by ca. 1 month due to weather circumstances. FC varieties were the same across locations, whereas maize varieties were selected location-specific for best results. During the season, all DCS and SCS were fertilized with slurry in the first four weeks of sowing (50–80 kg N ha^{-1}, location-specific) and hoed on average two-three times per season (See Table A2 for specificities). Maize harvest took place at BBCH 83–87 in September–October. In TRE during the first experimental year, all DCS systems had a shallow soil preparation before maize sowing, eliminating DCS NT from the experiment (and doubling DCS RT representation). Due to a frost event in 2021 in NEB, BBCH of some treatments did not reach desired levels. See Figure A1 and Tables A1–A3 for more details on locations and experimental conduct and Figure A2 for the experimental design. Among others, measured parameters may have site-specific sampling techniques to meet local capabilities. In the following section, discussed methods are generalized, referred to the smallest accuracy reached or in special cases, more options are presented with a superscript of the location abbreviation (TRE, NEB, PUC). All relevant location-specific operations are listed in Table A3.

Weather data were obtained from nearby weather stations (Deutscher Wetterdienst Lübeck; Landesbetrieb Landwirtschaft Hessen and Universität Kassel, Section of Soil Science Neu-Eichenberg; Bayerische Landesanstalt für Landwirtschaft Puch).

Crop performance, assessed as total harvested dry matter yield (DMY, t ha^{-1}), was estimated from first crop and maize DMY and expressed in t ha^{-1}. Hence, first crop DMY was measured on 0.75 m^2 biomass samples taken near full bloom and maize DMY was quantified from 1.5–2.25 $m^{2\ NEB}$ to 10–15 $m^{2\ TRE,\ PUC}$ silage-mature biomass cuts from the core of the plots. Differences relate to row width. Subsamples from the cuts were dried until no more weight loss occurred at 105 $°C^{TRE,\ NEB}$ or at 60 °C and were corrected to 105 $°C^{PUC}$. Dry matter content (DMC, %) was calculated from the weight difference between fresh and dry biomass.

Microsoft Excel 2016 and R version 4.0.4 [38] through RStudio version 1.4.1106 [39] were used for data organization, graphical presentation, and statistical analysis.

Following the suggestions of Schaarschmidt and Vaas [40] and Piepho et al. [41], a pseudo-one-factorial (generalized) mixed effect model ((G)LMM) was fitted for each location separately with treatment (n = 18) as fixed effect and year (n = 2) as random effect to estimate DMY and DMC averaged over two years. The general model structure is:

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

with the following indications: fixed + (1 | random). Models were fitted with normal distribution and identity link in the case of FC $DMY^{TRE,\ NEB}$, maize $DMY^{NEB,\ PUC}$, maize DMC, total harvested $DMY^{TRE,\ PUC}$. The response variable in the model for total harvested DMY^{TRE} was logarithmically transformed. Models for FC DMY^{PUC}, maize DMY^{TRE} and total harvested DMY^{NEB} utilized normal distribution and a logarithmic link (see Appendix B for further model specificities).

Relevant hypotheses were tested with specified contrasts, using orthogonal subsets of the modelled data with a focus on (I) DCS, DCMS versus SCS (pseudo-one-factorial), (II) *management* factor (NT, RT, Roll with Mixtures only) with additional *FC* or *row width* interactions and (III) *FC* factor in the Roll management only (V, V-Mix, P, P-Mix) with additional *row width* interaction. Main factor effect importance (*management*, *FC*, *row width*) and factor interactions are assessed graphically from contrasts. Mean/median estimates are proportional to number of observations with multivariate t (mvt) adjustment of the 95% confidence interval (CI) of estimated differences/estimates. The presented graphical results of focus (I) allow a further, in-depth investigation of multi-way factorial interactions. Three-way and higher interactions are often inconsistent and therefore, these are not going to be discussed in detail.

Additionally, a model to evaluate *year* and *year:treatment* interaction effects was established by assuming both *year* and *treatment* as fixed effect:

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

with the following indications: fixed + (1 | random). Year models were fitted with normal distribution and identity link, except for maize DMY^{TRE}, where a logarithmic link was utilized (see Appendix B for further model specificities). Tested hypotheses were built up similarly as mentioned above including an additional interaction with *year* (difference of differences for factor *year*) as described in Schaarschmidt and Vaas [40]. *Year:treatment* interactions were further assessed graphically.

Important packages for the statistical analysis were: lmerTest [42], glmmTMB [43], ggResidpanel [44], DHARMa [45], emmeans [46], RVAideMemoire [47]. A list of further packages and additional information on the analyses can be found in Appendix B.

3. Results

The two years under inspection had different weather conditions: 2019–2020 had warm winter months and a dry period before and at maize sowing in May-June. The summer stayed relatively dry in NEB, and especially in TRE. 2020–2021 was wet and cool near the maize sowing dates. The rest of the season was similar to long-term trends, except in NEB, where the precipitation was higher, and a cooler August was observed (Figure A1 and Table A2).

3.1. First Crop Yield

First crop dry matter yield (DMY, t ha^{-1}) was always lower for pure legumes (P, V) as for their mixtures. Pure legumes had varying DMY of 5.2–4.8 t ha^{-1} in TRE; 5.3–5.8 t ha^{-1} in NEB and 4.0–7.0 t ha^{-1} in PUC for V and P, respectively. However, mixtures yielded similar in each location: 6.3–6.8 t ha^{-1}; 7.5–7.6 t ha^{-1} and 6.3–6.8 t ha^{-1} for P-Mix–V-Mix in TRE, NEB and PUC. The Pure legume DMY in PUC is based mainly on the samples from 2019-20 (4 replicates), because in 2020-21 only one pooled sample was available.

3.2. Maize Yield and Dry Matter Content

Maize dry matter yield (DMY, t ha^{-1}) was the lowest in TRE with a range from 2.2 to 13.3 t ha^{-1}. In NEB, DMY ranged from 8.1 to 18.8 t ha^{-1} and in PUC, from 7.1 to 17.3 t ha^{-1}. Overall mean yields at the latter two locations were 200% and 160% of that in TRE. Overall mean yield difference compared to the first year was positive (+13.1%) in TRE, negative (−18.8%) in NEB and absent in PUC (−1.9%).

Focus I: DCS/DCMS maize yield compared to SCS were site-specific either significantly lower (TRE and biggest part of PUC) or statistically similar (NEB and partly PUC) (Figures 2 and 3 part I). The reduced row width in SCS had location-specifically different responses: no effect (TRE), non-significant (NS) yield increase (NEB) or NS yield decrease (PUC). Despite the differences to the 75 cm SCS, the factor effects behaved in a similar manner:

Focus II: *Management* was an important factor in the model at all locations, where RT produced in two out of three locations significantly higher yields than NT and Roll (Figure 3 part II). NT was either similar to Roll (NEB and PUC) or even worse (TRE). The two-way interaction of *management* with *FC* or *row width* was site-specific. In NEB, *FC* had an additive effect with V-Mix always being better. In TRE, this effect was also present, except in NT; and in PUC, in NT, whereas an opposite effect was seen in Roll. *Row width* mattered in the DCMS in TRE and NEB; and additionally, in DCS NT in TRE.

Focus III: *FC* had an important effect in DCMS. *FC group* was at all locations important (Figure 3 part III), but the species themselves just in TRE and PUC. *Row width* had an additive effect on *FC* in NEB, but only for the P(-Mix) treatments in TRE, whereas it had no observed effect in PUC.

Maize dry matter content (DMC, %) ranged from 19.3 to 37.1% in TRE ($\overline{x}$ = 29.4%, standard deviation ($\overline{sd}$) = 5.4%), from 25.9 to 35.5% in NEB ($\overline{x}$ = 30.9%, $\overline{sd}$ = 2.7%) and from 24.5 to 31.7% in PUC ($\overline{x}$ = 27.0%, $\overline{sd}$ = 1.9%) with a location-specific *year* difference: an increase in TRE (4.3 percentage point (pp), a decrease in NEB (8.7 pp) and PUC (11.9 pp) compared to the first year. The lower DMC across two years were connected to DCMS (TRE, 19.3–28.5%) or Mix DCMS (NEB, 25.9–28.2% and PUC, 24.5–25.6%). Therefore, highest differences among treatments originated from the *FC:management* interaction (Figure 4).

Focus I: DMC (%) of DCS/DCMS compared to SCS were site-specifically generally (NS) lower (TRE DCMS significantly lower) or rarely NS higher (NEB DCS RT, DCS NT 75 cm, Pure DCMS). The reduced row width in SCS had no observed effect on DMC. Despite the differences to the 75 cm SCS, factor effects behaved similarly, but with different magnitudes:

Focus II: *Management* was one of the most important factors in the model. RT and NT were similar at two locations (TRE, PUC), whereas at the third location (NEB), RT produced NS higher (3 pp) DMC than NT. Both RT and NT produced either similar DMC to Roll (PUC) or higher (TRE, NEB). The two-way interaction of *management* with *FC* or *row width* was site-specific and NS. In all locations, V-Mix Roll always produced higher DMC (max. 3 pp difference). In NEB, V-Mix was also preferable in RT and at PUC, in NT. The opposite effect was seen in TRE, where P-Mix promoted higher DMC in NT. *Row width* mattered at two locations: in TRE, where NT 50 cm increased DMC and in NEB, where DCS with 75 cm enhanced DMC (max. 3.6 pp difference).

Focus III: *FC* had an important effect in the DCMS. *FC group* was at all locations important, but the species themselves just in TRE. *Row width* had generally marginal or no detected effect across locations. The strongest *row width* effect was observed in TRE V(-Mix) with less than 2 pp difference.

3.3. Total Harvested Yield

Total harvested dry matter yield (DMY, t ha^{-1}) among the harvested DCS ranged from 8.0 to 15.1 t ha^{-1} in TRE; from 16.3 to 22.5 t ha^{-1} in NEB and from 16.5 to 20.1 t ha^{-1} in PUC (Figure 5). The share of maize from the yield ranged from 24.3 to 55.4% in TRE ($\overline{x}$ = 43.8, $\overline{sd}$ = 12.4); from 55.9 to 67.7% in NEB ($\overline{x}$ = 62.6, $\overline{sd}$ = 3.9) and from 46.3 to 54.9% in PUC ($\overline{x}$ = 51.3, $\overline{sd}$ = 3.7). Different FCs yielded similarly per location.

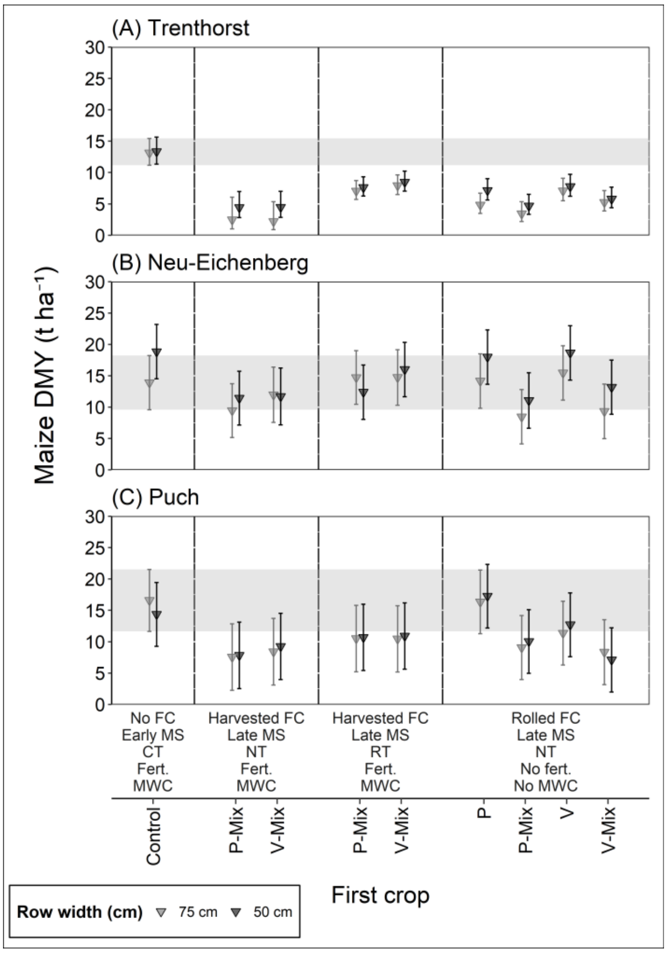

Figure 2. Maize dry matter yield (DMY, t ha^{-1}) at the different locations averaged over the experimental years 2019–2020 and 2020–2021. The x-axis shows the *first crop* factor (P = winter pea, P-Mix = winter pea and cereal mixture, V = hairy vetch, V-Mix = hairy vetch and cereal mixture) grouped by *management* (FC = first crop, MS = maize sowing, CT = conventional tillage, NT = no tillage, RT = reduced tillage, Fert. = fertilization, MWC = mechanical weed control). Colours indicate *row width*. Error bars represent the multivariate t adjusted 95% CI of the estimates. The grey background shows the 95% CI of the 75 cm SCS (Control) for a better comparison. Please note, that TRE had DCS NT treatments only in the second year.

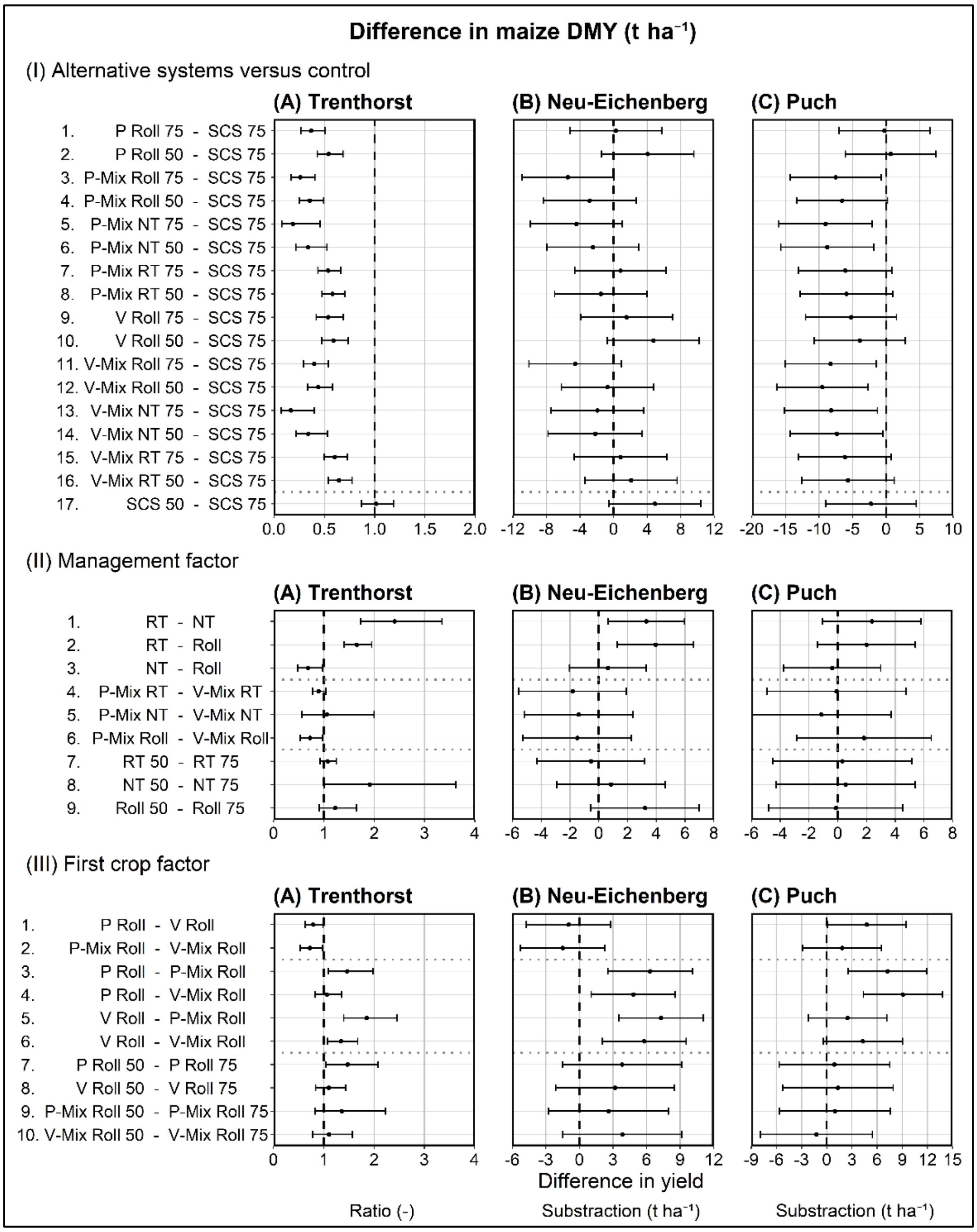

Figure 3. Differences in maize dry matter yield (DMY, t ha^{-1}) at the different locations averaged over the experimental years 2019–2020 and 2020–2021 with a focus on (I) Alternative systems versus control, (II) *Management* factor, (III) *First crop* factor. The y-axis shows the contrast in question, whereas differences are scaled 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 difference in median estimates as ratio (-) at TRE and in mean estimates as subtraction (t ha^{-1}) for NEB, PUC. The vertical dashed lines—at 1 for TRE and at 0 for NEB, PUC—show the H_0, where the difference of estimates in question is 0. Error bar shows the multivariate t adjusted 95% CI of the estimated difference. Thus, when this crosses the vertical dashed line (H_0), there is statistically no or NS difference of means/medians at $\alpha = 0.05$. Contrasts of each focus group are analyzed independently. Please note, that TRE had DCS NT treatments only in the second year.

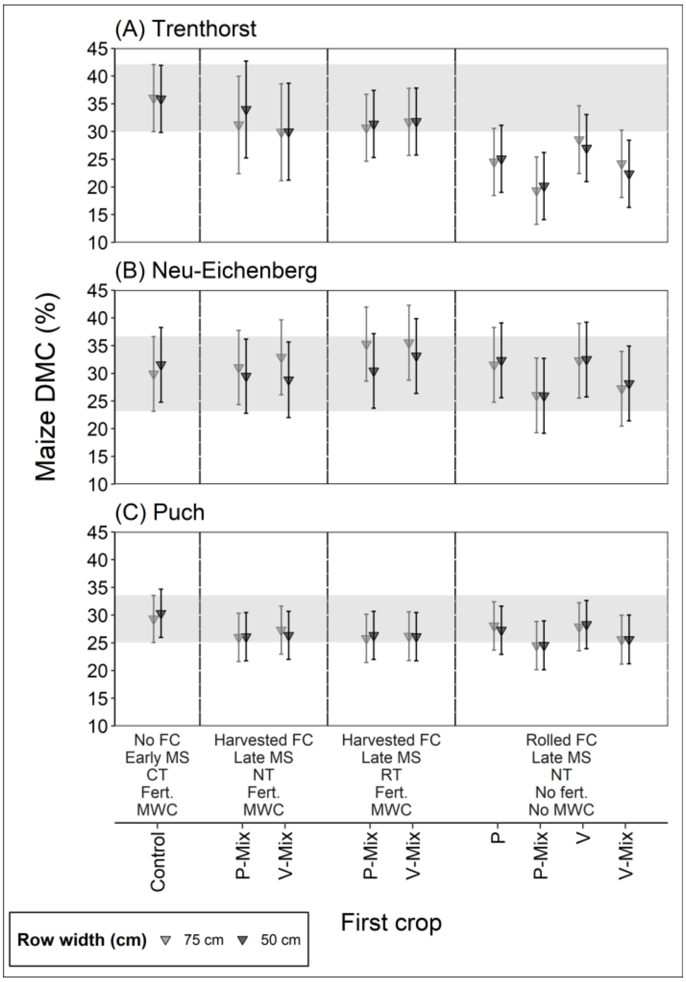

Figure 4. Maize dry matter content (DMC, %) at the different locations averaged over the experimental years 2019–2020 and 2020–2021. The x-axis shows the *first crop* factor (P = winter pea, P-Mix = winter pea and cereal mixture, V = hairy vetch, V-Mix = hairy vetch and cereal mixture) grouped by *management* (FC = first crop, MS = maize sowing, CT = conventional tillage, NT = no tillage, RT = reduced tillage, Fert. = fertilization, MWC = mechanical weed control). Colours indicate *row width*. Error bars represent the multivariate t adjusted 95% CI of the estimates. The grey background shows the 95% CI of the 75 cm SCS (Control) for a better comparison. Please note, that TRE had DCS NT treatments only in the second year and that the y-axis starts from 10%.

Focus I: DCS total harvested yield (t ha^{-1}, just harvested FC) was similar to SCS (TRE and DCS NT in PUC) or even (significantly) higher (NEB and DCS RT in PUC) (Figure 6 part I). As already shown in maize DMY (t ha^{-1}), factor effects behaved similarly across locations:

Focus II: *Management* was the most important factor at all locations in the model, where RT had (significantly) higher yields than NT or Roll (Figure 6 part II). NT produced either similar total harvested DMY to Roll (TRE) or became significantly higher (NEB and PUC). There was no two-way interaction of *management* with *FC* or *row width* across locations.

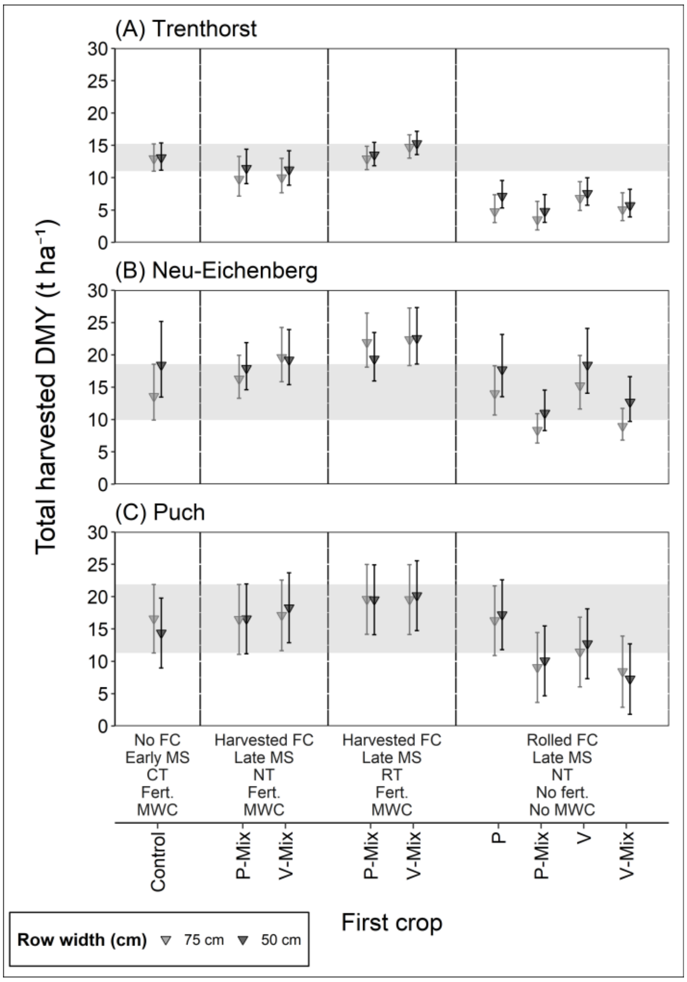

Figure 5. Total harvested dry matter yield (DMY, t ha^{-1}) at the different locations averaged over the experimental years 2019–2020 and 2020–2021. The x-axis shows the *first crop* factor (P = winter pea, P-Mix = winter pea and cereal mixture, V = hairy vetch, V-Mix = hairy vetch and cereal mixture) grouped by *management* (FC = first crop, MS = maize sowing, CT = conventional tillage, NT = no tillage, RT = reduced tillage, Fert. = fertilization, MWC = mechanical weed control). Colours indicate *row width*. Error bars represent the multivariate t adjusted 95% CI of the estimates. Th grey background shows the 95% CI of the 75 cm SCS (Control) for a better comparison. Please note, that TRE had DCS NT treatments only in the second year. For harvested FC, yields were 6.3–6.8 t ha^{-1} for TRE and PUC, 7.5–7.6 t ha^{-1} for NEB for P-Mix–V-Mix, respectively.

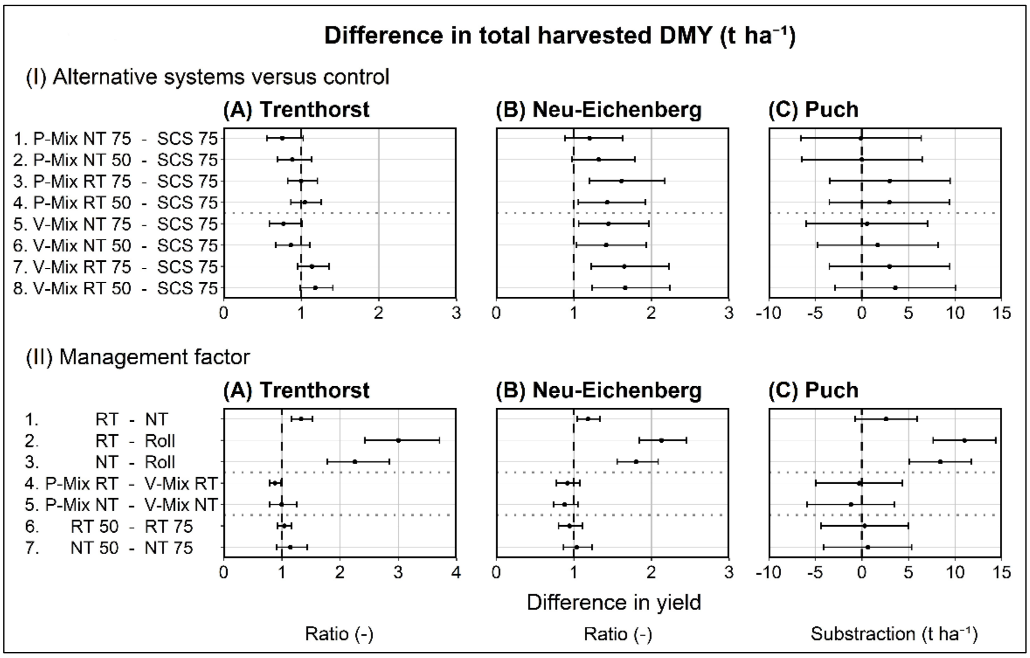

Figure 6. Differences in total harvested dry matter yield (DMY, t ha^{-1}) at the different locations averaged over the experimental years 2019–2020 and 2020–2021 with a focus on (I) Alternative systems versus control, (II) *Management* factor. The y-axis shows the contrast in question, whereas differences are scaled 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 difference in median estimates as ratio (-) at TRE, NEB and in mean estimates as subtraction (t ha^{-1}) at PUC. The vertical dashed lines—at 1 for TRE, NEB and at 0 for PUC—show the H_0, where the difference of estimates in question is 0. Error bar shows the multivariate t adjusted 95% CI of the estimated difference. Thus, when this crosses the vertical dashed line (H_0), there is statistically no or NS difference of means/medians at $\alpha = 0.05$. Contrasts of each focus group are analyzed independently. Please note, that TRE had DCS NT treatments only in the second year.

4. Discussion

Results varied across years and distinct locations for all measured parameters [41]. However, responses to *management*, *FC* and partly to *row width* were similar across locations, with a partially strong influence of *year* due to big differences in weather patterns at some critical phases of plant development/management (Figure A1).

Please note, that DCS NT treatments in TRE were only present in the second year, restricting the certainty about the effect of this treatment compared to the others. This is also apparent through the wider CI in Figures 2, 4 and 5.

4.1. First Crop Yield

First crop DMY was more influenced by *FC group* (Pure, Mix) than by comprised species, supporting similar suitability of the species—especially the legumes (P, V)—for studied pedological and climatical conditions [15,23,36]. Only one location (PUC) had a difference between pure legume yields (V: 4.0 t ha^{-1}; P: 7.0 t ha^{-1}; significant difference). Despite the 3.5 weeks later sowing date in the first year, the *FC:year* interaction was NS, suggesting that environmental and/or management conditions favour the studied pea variety over the hairy vetch variety at the location.

Mixtures seem to typically yield higher except in some years, where pure legumes may reach similar or even higher yields [15,16,19,20]. This could be the consequence of the complementary habitus of the mixed species [19] and the mentioned suitability of the present species in general. There were significant *FC group:year* interactions in TRE

(2019–2020 pure legumes had slightly higher yields as mixtures with a very strong *FC:year* interaction for P-Mix) and PUC (2020–2021 mixtures yielded similar to P), suggesting a high relevance of *location* (*environment:management*). Weather patterns may explain the observed differences: 2020–2021 with cooler temperatures may have favoured cereal partners in the mixtures, possibly related to N mineralization [48] and acquisition processes under lower temperatures.

4.2. Maize Yield and Dry Matter Content

Because the two years under inspection differed throughout the maize cropping season, *year:treatment* interactions may be relevant for maize DMY and DMC. The most important differences were observed near maize sowing: In 2020, the weather was drier, whereas in 2021, it was cooler and wetter at all locations. These differences generally influenced sowing dates and further possibilities of MWC, which possibly affected final maize yields (Table A2).

Maize DMY was foremost influenced by the *system* (SCS, DCS, DCMS) and *system:location* interaction. Each location had different relation of the alternative systems to control (TRE: significantly lower, NEB: similar, PUC: lower). These differences may come from the optimization of the production for one (SCS) or two crops (DCS, DCMS) and this is strongly related to the number of crops and not to the sowing date of maize *per se*. This is strongly supported by similar yields in both early and late sown SCS treatments at TRE and PUC (data now shown). Concerns about nutrient- and water-use, the length of seasonal vegetative window in DCS, DCMS were worrying researchers for a longer time [1,7,14,19] and that yields may decrease in such systems [1,16,23], but there are some results indicating that similar yields as in SCS are reachable [6,25].

Both *management* (only Mix FC group) and *FC group* (only Roll management) were influencing yields to a higher extent. Differences among *management* (RT, NT, Roll) indicate a strong influence of soil conditions near the sowing date on the silage maize yield. Only the magnitude of differences changes with locations, but the general picture shows that a yield pattern of RT $\geq$ Roll $\geq$ NT is consistent over the years and locations. A yield reduction effect of NT management is common [21]. However, in this experiment, the tillage practices differ only right before maize sowing. Therefore, a short-term effect of soil disturbance before sowing on the soil water-, temperature- and mineralization-complex may explain the differences among all three factor levels. Mineralization is increased among others by soil disturbance (exposure), aeration and temperature increase [48] and these effects are closely related to increased soil evaporation due to tillage operations [4,31,49]. Additionally, residues in NT or a mulch layer potentially decrease mineralization rates due to the lower daily temperatures, more moisture preservation connected to a reduced evaporation rate [14,30,31,49]. Difficulties of optimal N mineralization rates in the early season of organic systems [32–35] seem to be confirmed in the Roll management. However, the yield differences in the *FC group* suggest that less, easier decomposable, more N rich biomass may overcome these boundaries [15,19,23,28] to an at-least-comparable extent as RT after FC harvest (Figures 2 and 3). The present results show that all locations profit from the enhancing effects on soil water-, temperature- and mineralization-complex through tillage or pure legume mulch. However, the effects are so intercorrelated that the identification of the most important fragment is problematic, furthermore, it is strongly connected to weather and soil characteristics. Additionally, BBCH, plant height and leaf chlorophyll (SPAD-502) measurements from one location (NEB) may provide further support on the observed influence of soil conditions on plant development (Appendix C and Table A4): In 2019–2020, BBCH among DCS, DCMS were similar with an initial slight lag in Roll management. This stayed marginal but consistent throughout the season. Elongation started ca. 1 week earlier in the Pure Roll treatments than others. However, in 2020–2021 (wet, cool), additional differences among tillage systems were observed (RT > NT). Elongation started ca. 1 week earlier in Pure Roll than in Pure Mix, and in RT than in NT under 50 cm row width. Under mulch management, a slight hindering of emergence from the thick mulch layer was detected in all locations, which is confirmed by the BBCH measurements. However, plant height and leaf chlorophyll content ca. 4 weeks after the sowing date only showed slight differences. As time proceeded, differences in all three parameters showed better plant development in RT and Pure Roll than in NT and especially in Mix Roll (data from NEB only). The mechanisms behind are naturally connected to that of N mineralization and available nutrient solutes at emergence and establishment. The effects between Mix Roll and Pure Roll were more pronounced in the second year. Whereas, differences between RT and NT were only present in the second year. These are also pointing out the difficulties to establish and maintain optimal soil conditions for crop development in this critical phase [14,21,23].

Two-way interactions of *management* with *FC* and *row width* (Figure 3 part II) or *FC* with *row width* (Figure 3 part III) were site-specific. The strongest interactions were observed in TRE, where yields in DCS, DCMS were the most reduced compared to SCS. These may indicate a compensation mechanism of increased yield with reduced *row width* in the NT management (difference ratio: 1.9) and additionally in the less successful P(-Mix) Roll management (mean difference ratio: 1.4). *FC* effect in TRE was only present in the Roll management. This is connected to the *FC* effect at 75 cm row width and the stronger response of P-Mix to *row width*, confirming further the compensation mechanism of *row width* in less successful factor combinations (P-(Mix) Roll). In NEB, both *FC* (V-Mix) and *row width* (50 cm) had a nearly pure additive effect on maize yield (Figure 3 parts II and III). This is not apparent in the results for RT and NT, while the yield reduction under 50 cm row width in 2020–2021 (13 days later sown, no MWC; see Table A2) was nearly identical to the yield increase under reduced row width the year before. On the contrary, PUC presented no detected *row width* but an *FC* interaction, where P(-Mix) in the mulched systems were always enhancing maize DMY compared to V(-Mix). This may be due to the more optimal development of P and therefore a better N_2 fixation capacity in pure or mixed stands at PUC, rather than purely by total N concentration related to biomass yield, as observed by Holderbaum et al. [15] because first crop DMY in mixtures was similar with no observed *FC:year* interaction. Additionally, there was a strong influence of *year* on maize yields in DCMS: 2019–2020 showed very high yields (similar to SCS) in the P Roll, but very low yields in all other Roll treatments (V was resown), especially in V-Mix Roll. On the other hand, 2020–2021 displayed similar trends as at the other locations, where Pure DCMS generated higher yields than the mixtures—here as high as SCS. Presented results add to the observed mixed effect of reduced *row width* on silage and grain yield in irrigated or rainfed, conventionally managed systems [50–52].

Maize DMC was in acceptable ranges (30–40%—[53,54]) only in SCS and DCS, and location-specifically in Pure DCMS (NEB). All (Mix) DCMS had lower DMC, making these materials mostly unacceptable for silage production [54,55], resulting in poor fermentation patterns and excessive seepage [54,56]. However, DMC of maize plants was highly influenced by *year*. At two locations—NEB and PUC—, treatments in the first year were generally in good range (29.0–39.5%), but low DMC was observed in the second, cooler year (PUC: 19.2–22.5%, NEB: 22.1–27.7% in DCMS, DCS 50 cm).

This *year* effect may be explained by the suboptimal conditions at maize sowing in the second year: The cold and wet weather delayed FC maturity, soil drying and warming, which delayed sowing and/or emergence of maize with partially inadequate furrow closure and possible soil compaction, especially without tillage operations. Due to the late sowing dates, feeding bird-damage also occurred at two locations (TRE, NEB). As a correction measure, DCMS treatments were resown in TRE and DCS 50 cm treatments in NEB. Reasons for the higher damage by birds in the 50 cm row width compared to 75 cm row width in NEB with the same plant density is unknown. Furthermore, the wet weather in NEB even hindered MWC applications in narrow row width DCS. At TRE, *year* effect was only for DCS relevant, and the lowest DMC was in both years in the (Mix) Roll treatments.

Next to *year*, *system* had a strong influence on DMC, which is partially incorporated into *management*. However, this effect is not due to the sowing date *per se* (data from

TRE, PUC and not shown), but rather to the management conditions which influence the development and seasonal vegetative window in a similar manner as they influence maize DMY, but with a stronger difference between DCS and DCMS. Results suggest that as conditions are getting wetter and cooler at sowing—related to location (TRE) and/or seasonal variation (NEB, PUC)—especially Mix DCMS systems are risking too low DMC. In such conditions, earlier maturing maize varieties may optimize DCS, and especially DCMS systems. Additionally, the alteration of management from DCMS to DCS, especially to DCS RT may further secure adequate DMC for silage production.

4.3. Total Harvested Yield

Total harvested DMY was in the range of or even higher than SCS without the yearly variation reducing the effectiveness of DCS compared to SCS. This supports the risk reduction of DCS [1,8]. Differences came from *management* (only Mix FC) in this case, and there seemed to be no *FC* and *row width* effect or interaction on total harvested DMY. These are not similar to the maize DMY factor effects, which is partially because the analysis of total harvested DMY does not make any difference among species contributing to final yield: FC yields did not differ to high extents, and they were added on top of maize yields. Therefore, the biggest part of variation explained among treatments was connected to *management*, and further effects are therefore minimized in the model. *Management* follows a similar pattern as maize yields, but with DCS being better as DCMS: RT > NT ≥ Roll.

5. Conclusions

The wide scope of factor combinations in this study (*FC, management—FC use, tillage, additional slurry fertilization, mechanical weed control—, row width)* allows a sound exploration of possible factor effects and interactions. A high variation among environments (years, locations) occurred, but patterns were similar across locations: The number of crops had a high influence, followed by *management* and *FC*. FC DMY was rather influenced by *FC group* than by comprised species, with mixtures generally yielding higher. Maize DMY in DCS, DCMS was lower-to-comparable to SCS with the following factor patterns: RT ≥ Roll ≥ NT; Pure > Mix. *Row width* effect was marginal and inconsistent. Maize DMC was location- and season-specifically below the acceptable range, especially in DCMS; and with RT ≥ NT ≥ Roll and Pure ≥ Mix patterns. Total harvested DMY in DCS were similar-to-greater as in SCS with RT ≥ NT ≥ Roll pattern. No further *FC* or *row width* effect or interaction was observed. Results suggest differences occurring from the optimization of farming operations and resources for one (SCS) or two crops (DCS, DCMS) with strong effects at early development and on the season length. *FC use* and *tillage* generates differences probably through influencing the soil water-, temperature- and mineralization-complex. DCS RT and DCMS Pure offered the best DMY with improved soil protection and tillage reduction in the silage maize part of the rotation under organic management. However, alternative systems, especially under NT and (Mix) Roll are less suited with the studied maize maturity classes, especially in cool and wet spring, because of a potentially slower establishment of maize plants and a therefore shorter season. System improvement may be achieved by system-oriented variety selection and breeding in both FC and maize, the improvement of machinery and the establishment of a crop rotation suited for such systems. Further research comprising a similar scope as in this experiment, focusing on soil conditions and their influence on plant emergence and early plant establishment; a quantitative analysis of the assumed soil protection; and the effect of alternative systems under a full rotation are required to further evaluate the viability of these systems.

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Appendix A

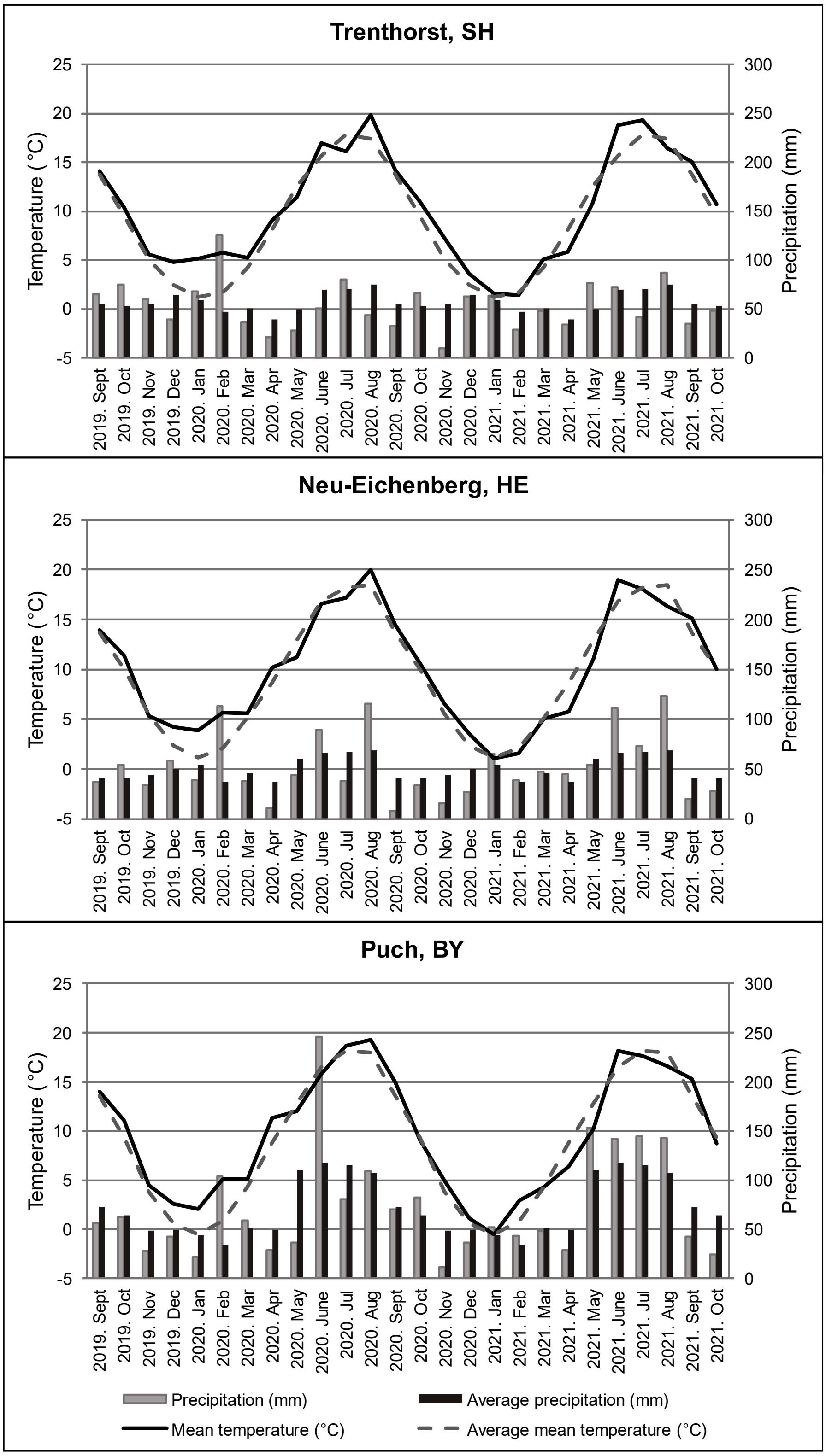


Figure A1. Monthly mean temperature (°C) and monthly accumulated precipitation (mm) from September 2019 until October 2021 compared to the monthly averages from long-term measurements (1985–2021 for Trenthorst, 1971–2021 for Neu-Eichenberg and 1995–2021 for Puch) for the three locations.

Table A1. Long-term yearly mean temperature and cumulative precipitation and in the two years across the three experimental locations (TRE = Trenthorst, NEB = Neu-Eichenberg, PUC = Puch). Long-term measurements are from 1985–2021 for TRE, from 1971–2021 for NEB and from 1995–2021 for PUC.

	Long-Term			**2019–2020**			**2020–2021**		
Location	**TRE**	**NEB**	**PUC**	**TRE**	**NEB**	**PUC**	**TRE**	**NEB**	**PUC**
Yearly mean temperature (°C)	9.1	9.6	8.9	10.5	10.5	10.0	9.5	9.3	8.7
Yearly precipitation (mm)	690	614	869	624	573	884	630	679	934

Table A2. Preceding crop, sowing and harvesting dates, hoeing (count) and fertilization (amount and date) both for the relevant treatments (DCS, SCS) in the locations over two years. (TRE = Trenthorst, NEB = Neu-Eichenberg, PUC = Puch; SCS = sole cropped system, DCS = double cropping system, DCMS = double cropped, mulched system, V = hairy vetch, 75 cm = 75 cm row width of maize, 50 cm = 50 cm row width of maize).

Location	**Year**	**Preceding Crop**	**First Crop**		**Maize**		**Hoeing**	**Fertilization (kg ha^{-1} and Date)**	**Distinct Factors**
			Sowing	**Harvest**	**Sowing**	**Harvest**			
TRE	2019–2020	spring wheat	-		07–08.05.	30.09.	3	80 kg N ha^{-1}, 23.06.	SCS
	2019–2020		31.10.	02.06.	09–10.06.	12-13.10.	3	80 kg N ha^{-1}, 23.06.	DCS, DCMS
	2020–2021	spring wheat	-		03.06.	27.10.	1	85 kg N ha^{-1}, 02.06.	SCS
	2020–2021		21.09.	07–08.06.	09.06.	27.10.	1	57 kg N ha^{-1}, 08.06.	DCS
	2020–2021		21.09.	07.06.	23.06.	27.10.	-	-	DCMS
NEB	2019–2020	phacelia	-		06.05.	17.09.	2	80 kg N ha^{-1}, 22.06.	SCS
	2019–2020		-		29.05.	17.09.	2	80 kg N ha^{-1}, 22.06.	SCS, row 1
	2019–2020		14.10.	27.05.	29.05.	11–12.10.	2	80 kg N ha^{-1}, 22.06.	DCS, DCMS
	2020–2021	mustard	-		08.05.	20.09.	2	80 kg N ha^{-1}, 28.06.	SCS
	2020–2021		13.10.	01.06.	02.06.	13.10.	1	80 kg N ha^{-1}, 28.06.	DCS 75 cm
	2020–2021		13.10.	09.06.	10.06.	13.10.	-	-	DCMS
	2020–2021		13.10.	01.06.	15.06.	13.10.	0	80 kg N ha^{-1}, 28.06.	DCS 50 cm
PUC	2019–2020	winter wheat	-		28.04.	22.09.	3	74 kg N ha^{-1}, 05.27.	SCS
	2019–2020		01.10.	26.05.	28.05.	22.09.	2	46 kg N ha^{-1}, 05.27.	DCS, DCMS
	2019–2020		26.10.	26.05.	28.05.	22.09.	-	-	DCMS V
	2020–2021	spelt	-		15.06.	28.09.	2	80 kg N ha^{-1}, 14.07.	SCS
	2020–2021		06.10.	14.06.	15.06.	28.09.	2	40 kg N ha^{-1}, 14.07.	DCS, DCMS

Table A3. Crop varieties, sowing and harvest sampling parameters across locations. (P = winter pea, P-Mix = winter pea-cereal mixture, V = hairy vetch, V-Mix = hairy vetch-cereal mixture; SCS = sole cropped system, DCS = double cropping system, DCMS = double cropped, mulched system).

Crop	**Variety**	**Share in Mix (%)**	**Sowing Density**	**Harvest Parameters**
P	EFB 33	-	80 m^{-2}	1–25 m^{2} ** $^{\mathrm{TRE}}$ 0.75 m$^{2\ \mathrm{NEB}}$ 4.5–27 m^{2} ** $^{\mathrm{PUC}}$ 5 cm height
P-Mix	EFB 33 + Tulus (2019–2020) * Inspectior (2020–2021) *	40:60$^{\mathrm{TRE,\ PUC}}$ 35:65$^{\mathrm{NEB}}$	32:240 m$^{-2\ \mathrm{TRE}}$ 28:205 m$^{-2\ \mathrm{NEB}}$ 32:240 m$^{-2\ \mathrm{PUC}}$	
V	Ostsaat-Dr. Baumanns	-	250 m$^{-2\ \mathrm{TRE}}$ 130 m$^{-2\ \mathrm{NEB}}$ 250 m$^{-2\ \mathrm{PUC}}$	

Table A3. *Cont.*

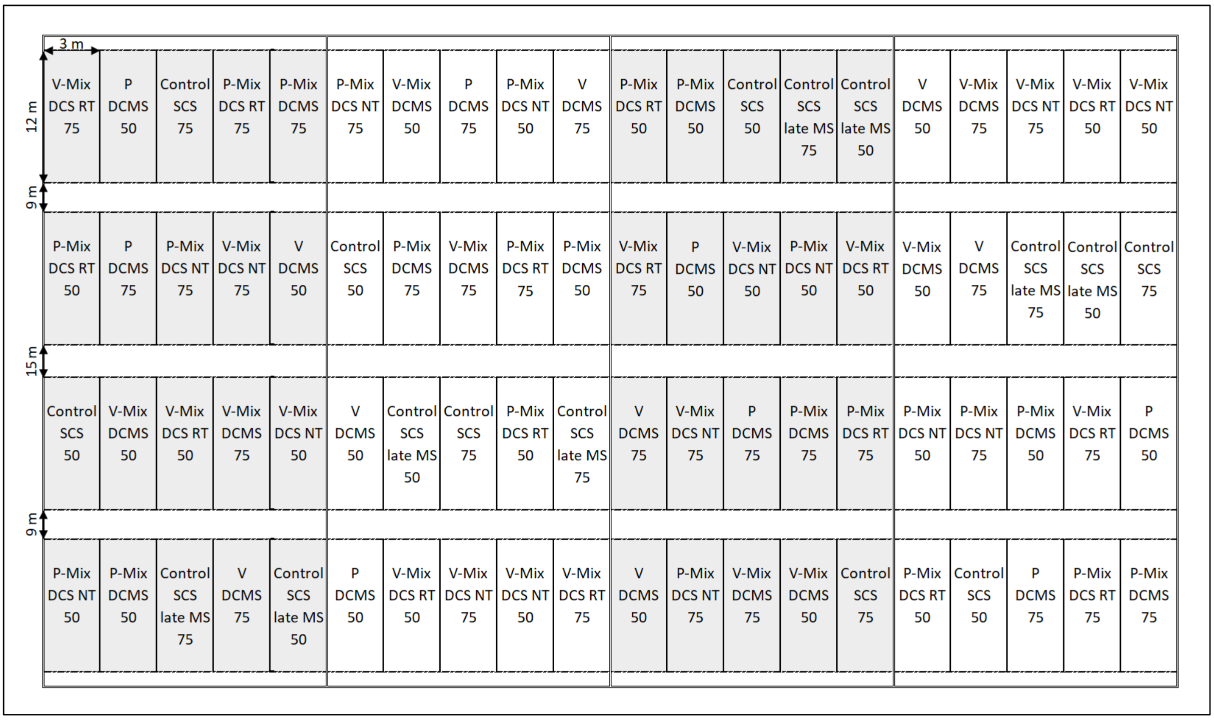
Crop	Variety	Share in Mix (%)	Sowing Density	Harvest Parameters
V-Mix	Ostsaat-Dr. Baumanns + Inspector	40:60$^{\text{TRE, PUC}}$ 35:65$^{\text{NEB}}$	100:240 m$^{-2\ \text{TRE}}$ 46:205 m$^{-2\ \text{NEB}}$ 100:240 m$^{-2\ \text{PUC}}$	
Maize (SCS)	Keops (210)$^{\text{TRE, PUC}}$ Farmfire Öko (230)$^{\text{NEB}}$ Geoxx (240)$^{\text{PUC}}$		10 m^{-2}	10–15 m$^{2\ \text{TRE}}$ 13.5 m$^{2\ \text{PUC}}$ 15–20 cm height$^{\text{TRE, PUC}}$ 1.5–2.25 m$^{2\ \text{NEB}}$ 10–15cm height$^{\text{NEB}}$
Maize (DCS, DCMS)	Perez KWS (160)$^{\text{TRE}}$ Cathy (210)$^{\text{NEB}}$ Keops (210)$^{\text{PUC}}$		10 m^{-2}	

* A change was implemented due to the late blooming date of triticale, which promoted regrowth after harvest/roll. ** The smaller sample size relates to DCMS Pure, whereas the bigger one is the sample size in DCS. TRE = Trenthorst, NEB = Neu-Eichenberg, PUC = Puch.

Appendix B

To keep the specifications of the experimental layout and statistical analysis cohesive, some parts of the Materials and Methods are shortly repeated.

The field experiment was conducted in a row-column design (4 × 20 units with 30 m^2 net plots) with four replicates. Each row was a complete replicate. Exact location of treatments in the row- and column-wise randomization—grouping 5 columns into another complete block perpendicular to rows—changed per year and location. As an example, Figure A2 shows the experimental layout in Trenthorst from 2020–2021. Net plots (after excluding the plot edges) were 3 m wide and 10 m long in each location, and a road separated each row, allowing the machinery to pass. Additional edge plots were located at both ends of the rows (not shown in Figure A2).



V-Mix DCS RT 75	P DCMS 50	Control SCS 75	P-Mix DCS RT 75	P-Mix DCMS 75	P-Mix DCS NT 75	V-Mix DCMS 50	P DCMS 75	P-Mix DCS NT 50	V DCMS 75	P-Mix DCS RT 50	P-Mix DCMS 50	Control SCS 50	Control SCS late MS 75	Control SCS late MS 50	V DCMS 50	V-Mix DCMS 75	V-Mix DCS NT 75	V-Mix DCS RT 50	V-Mix DCS NT 50
P-Mix DCS RT 50	P DCMS 75	P-Mix DCS NT 75	V-Mix DCS NT 75	V DCMS 50	Control SCS 50	P-Mix DCMS 75	V-Mix DCMS 75	P-Mix DCS RT 75	P-Mix DCMS 50	V-Mix DCS RT 75	P DCMS 50	V-Mix DCS NT 50	P-Mix DCS NT 50	V-Mix DCS RT 50	V-Mix DCMS 50	V DCMS 75	Control SCS late MS 75	Control SCS late MS 50	Control SCS 75
Control SCS 50	V-Mix DCMS 50	V-Mix DCS RT 50	V-Mix DCMS 75	V-Mix DCS NT 50	V DCMS 50	Control SCS late MS 50	Control SCS 75	P-Mix DCS RT 50	Control SCS late MS 75	V DCMS 75	V-Mix DCS NT 75	P DCMS 75	P-Mix DCMS 75	P-Mix DCS RT 75	P-Mix DCS NT 50	P-Mix DCS NT 75	P-Mix DCMS 50	V-Mix DCS RT 75	P DCMS 50
P-Mix DCS NT 50	P-Mix DCMS 50	Control SCS late MS 75	V DCMS 75	Control SCS late MS 50	P DCMS 50	V-Mix DCS RT 50	V-Mix DCS NT 75	V-Mix DCS NT 50	V-Mix DCS RT 75	V DCMS 50	P-Mix DCS NT 75	V-Mix DCMS 75	V-Mix DCMS 50	Control SCS 75	P-Mix DCS RT 50	Control SCS 50	P DCMS 75	P-Mix DCS RT 75	P-Mix DCMS 75

Figure A2. Experimental layout in Trenthorst (2020–2021). Treatments are indicated by *first crop* (Control, P = winter pea, P-Mix = winter pea and cereal mixture, V = hairy vetch, V-Mix = hairy vetch and cereal mixture), *system:management* (SCS = sole maize cropping system, DCS NT = double cropping system no-till, DCS RT = double cropping system reduced tillage, DCMS = double cropped, mulched system) and *row width* (75 cm and 50 cm) factors. In this location, two additional treatments were included (SCS with late maize sowing (MS)). Randomization followed rows (complete block) and a set of columns (a group of every five columns gives another complete block, perpendicular to rows). Blocks over columns are indicated with double lines and further by a slight change in background colour. The exact plot size (gross) was 3 m × 12 m, whereas the net plot size was 3 m × 10 m with 9 m to 15 m separation among rows.

The general model structures with fixed *treatment* effect (n = 18) and random *year* effect (n = 2) for maize DMY, total DMY and maize DMC is as follows:

$$\text{response} = \text{treatment} + \text{year} + (1 \mid \text{year:treatment}) + (1 \mid \text{year:row}) + (1 \mid \text{year:column}) \tag{A1}$$

with the indications: fixed + (1 | random). Models to compare yearly variations (year model) only differ in threating *year*, and therefore the *year:treatment* interaction, as fixed effects:

$$\text{response} = \text{treatment} + \text{year} + \text{year:treatment} + (1 \mid \text{year:row}) + (1 \mid \text{year:column}) \tag{A2}$$

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

All treatments per location were involved in the analysis to estimate the experimental error structure as accurately as possible. This includes 2 additional treatments in TRE (Figure A2), 8 in NEB, and 1 in PUC. In NEB, the 8 treatments were incorporated as partial split-plots in the DCS treatments, dividing the rows perpendicularly into two. The dividing factor was *additional slurry fertilization* (yes-no). Therefore, the general model structure for NEB with random *year* effect is:

$$\text{response} = \text{treatment} + \text{year} + (1 \mid \text{year:treatment}) + (1 \mid \text{year:row}) + (1 \mid \text{year:column}) + (1 \mid \text{year:row:column}) \tag{A3}$$

and with fixed *year* effect is:

$$\text{response} = \text{treatment} + \text{year} + 1 \mid \text{year:treatment} + (1 \mid \text{year:row}) + (1 \mid \text{year:column}) + (1 \mid \text{year:row:column}) \tag{A4}$$

with the indications: fixed + (1 | random). PUC had an additional variety for early sown maize (Table A3). This difference was ignored in the analysis. Models had REML specification, except for maize DMY and total DMY in TRE, DMC in PUC; here ML estimations were used.

Modelling FC DMY only assessed *row* from the layout, as only a subset of the plots were sampled. The model averaging over the two years is:

$$\text{response} = \text{treatment} + \text{year} + (1 \mid \text{year:treatment}) + (1 \mid \text{year:row}) \tag{A5}$$

The model with fixed *year* effect is:

$$\text{response} = \text{treatment} + \text{year} + \text{year:treatment} + (1 \mid \text{year:row}) \tag{A6}$$

with the indications: fixed + (1 | random). In NEB, FCs in 2020–2021 were sampled at different times for DCS and DCMS. Total DMY included the estimates from sampling at harvest for DCS, whereas FC DMY of different FCs was compared from sampling before FC rolling in DCMS systems.

Models for FC DMY (t ha^{-1}) were based on Gaussian distribution with identity link for TRE and NEB, and with logarithmic link for PUC. Due to strong heteroscedasticity, the model for NEB was with 2 variance patterns fitted (*FC group*). For maize DMY (t ha^{-1}) models were based on Gaussian distribution with logarithmic link for TRE and with identity link for NEB and PUC. For PUC, the model was with 6 variance patterns fitted (*year:FC use*). For maize DMC (%), all models were based on Gaussian distribution with identity link, but for PUC, 2 variance patterns were fitted (*year*). For total harvested DMY (t ha^{-1}), they were based on logarithmic-transformed response for TRE, on a Gaussian model with logarithmic link for NEB and with identity link for PUC. In this case, NEB was employing 4 variance patterns (*FC use:tillage*). Total harvested DMY was modelled without discriminating between FC and maize yield. Therefore, SCS and DCMS may have slightly different yields as in the maize DMY model.

Year models for FC DMY (t ha^{-1}) were based on Gaussian distribution with identity link for all locations. Due to strong heteroscedasticity, the model for TRE was with 2 variance patterns fitted (*FC group*). For maize DMY (t ha^{-1}) models were based on Gaussian distribution with logarithmic link for TRE and with identity link for NEB and PUC. For PUC, the model was with 6 variance patterns fitted (*year:FC use*). For maize DMC (%), all models were based on Gaussian distribution with identity link, but for PUC, 8 variance patterns were fitted (*year:management*). For total harvested DMY (t ha^{-1}), they were based on Gaussian distribution with identity link for all locations. In this case, PUC was employing 3 variance patterns (*harvest* (yes, no, roll)). Total harvested DMY was modelled without discriminating between FC and maize yield.

Estimates of means and linear contrasts are analysed using the Kenward-Roger approximation for the denominator degrees of freedom and multivariate t (mvt) adjustment for the 95% CI. Where replicates were inbalanced across treatments due to missing observations (e.g., in TRE), levels are weighted in proportion to the number of observations. Contrast-hypotheses focused on alternative systems versus control and main factor effects (*FC*, *management*, their interactions with *row width* or *FC*). All focuses were analyzed separately due to the nature of the questions. Tests were conducted before back-transformation, when relevant.

Factor effect importance (*management, FC, row width*) and factor interactions were assessed graphically from linear contrasts. An example is Figure 3 part II contrasts 1–3, which summarizes the *management* effect, whereas contrasts 4–6 assess the *management:FC* interactions. If the latter three differences are near the H_0, *FC* would have nearly no effect on *management*. If these differences behave differently from each other, *management:FC* interactions are present. The extent of this interaction may be estimated by inspecting the x-axis unit. This method does not test the statistical significance of the interactions.

Year, year:treatment interactions were also assessed graphically and statistically by calculating the difference of differences, as described in Schaarschmidt and Vaas [40]. An example equation for the *year:management* interaction inspecting the influence of *year* on the difference between RT and NT would be:

$$[(RT_1 - NT_1) - (RT_2 - NT_2)] = [RT_1 - NT_1 - RT_2 + NT_2] \tag{A7}$$

where subscript refers to *year*. Equation (7) shows that the difference of differences is capable of testing interactions statistically but fails to reveal which element(s) are responsible for the significant differences when they occur.

List of packages used and not mentioned in the Materials and Methods section are: (1) For data preparation: readxl [57], dplyr [58], janitor [59], VIM [60]. (2) For data presentation: ggplot2 [61], patchwork [62], GGally [63].

Appendix C

In Neu-Eichenberg (NEB), development stage, leaf chlorophyll content and height were repeatedly measured in a two-week rhythm. Development stage was assessed on three random plants per plot according to the BBCH-identification key. SPAD measurements were taken with a SPAD-502 device from three random plants per plot at three points of the youngest fully developed leaf. Plant height (cm) in the vegetative phase was measured for three randomly selected plants from soil level to the highest point of the youngest, at least 50% developed leaf. Each repetition was averaged to one plot value.

Table A4. BBCH, leaf chlorophyll content (SPAD) and height measurements over the first 5 weeks of plant development in NEB. Averages of raw data is shown. Measurement dates are as follows: t1 = 10.06.2020 and 28.06.2021; t2 = 19.06.2020 and 02.07.2021; t3 = 25.06.2020 and 09.07.2021; t5 = 08.07.2020 and 22.07.2021.

Year	Treatment	BBCH_{t1}	BBCH_{t2}	BBCH_{t3}	BBCH_{t5}	SPAD_{t3}	SPAD_{t5}	Heigh_{t3} (cm)	Heigh_{t5} (cm)
2019–2020	SCS	13	15	14	18	36	38	38.5	88.8
	DCS RT	11	12	13	16	32	39	20.1	47.6
	DCS NT	11	13	13	16	33	35	20.3	46.3
	DCMS Pure	0	12	13	17	35	38	20.5	49.8
	DCMS Mix	0	11	12	15	33	33	18.9	39.2
2020–2021	SCS	16	31	32	35	40	41	84.4	174.6
	DCS RT 75	16	16	19	34	42	43	54.8	123.9
	DCS NT 75	14	15	16	30	34	39	43.8	91.7
	DCMS Pure	12	14	14	30	34	44	28.0	74.5
	DCMS Mix	11	12	13	16	31	35	25.6	60.1
	DCS RT 50	13	14	15	30	34	43	31.9	82.8
	DCS NT 50	12	13	14	17	29	32	23.7	65.9

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