Ingrid Claß-Mahler[1], Beate Zimmermann[1], Wilfried Hermann[2], Jürgen Schwarz[3], Hans-Peter Piepho[4], Iris Lewandowski[5], Hella Kehlenbeck[3], Enno Bahrs[1]

Yield Potential of Cropping Systems without Chemical Synthetic Plant Protection Products in NOcsPS field trials in Germany

Affiliations
[1]University of Hohenheim, Farm Management (410b), Stuttgart, Germany.
[2]University of Hohenheim, Agricultural Experiment Station (400), Stuttgart, Germany.
[3]Julius Kühn Institute (JKI) – Federal Research Centre for Cultivated Plants, Institute for Strategies and Technology Assessment, Kleinmachnow, Germany.
[4]University of Hohenheim, Biostatistics (340c), Stuttgart, Germany.
[5]University of Hohenheim, Biobased Resources in the Bioeconomy (340b), Institute of Crop Science, Stuttgart, Germany.

Correspondence
Dr. Ingrid Claß-Mahler, University of Hohenheim, Farm Management (410b), Schwerzstraße 44, 70599 Stuttgart, email: Ingrid.classmahler@uni-hohenheim.de

Abstract

In endeavors to manage agricultural cropping systems without the application of chemical-synthetic plant protection products (CSPs), one of the greatest challenges is ensuring yield performance. The literature provides a wealth of data on organic farming yields and the gap between organic and conventional systems, but little knowledge on the yield performance of cropping systems that use mineral fertilizers but not CSPs. This paper presents the first results of field trials at two locations in Germany comparing cultivation systems that are free of chemical-synthetic plant protection, but use mineral fertilizers, with both conventional and organic cropping systems. These system trials are part of the joint research project "Agriculture 4.0 without chemical-synthetic plant protection (NOcsPS)". Initial results show that CSP-free cultivation systems generally achieve lower yields than conventional systems, but considerably higher yields than organic systems.

Keywords

pesticide-free, sustainable farming systems, mineral fertilizer, equidistant seeding, weed control, biostimulants, agroecology

Zusammenfassung

Beim Verzicht auf chemisch-synthetische Pflanzenschutzmittel ist die Sicherstellung der Ertragsleistung in landwirtschaftlichen Anbausystemen eine der größten Herausforderungen. In der Literatur finden sich viele Daten über die Erträge im ökologischen Landbau und die Ertragslücke zu konventionellen Systemen, aber es ist nur wenig bekannt über die Ertragsleistung von Anbausystemen, die keine chemisch-synthetischen Pflanzenschutzmittel verwenden, aber Mineraldünger einsetzen. In diesem Beitrag werden die ersten Ergebnisse von Feldversuchen vorgestellt, in denen Anbausysteme ohne Einsatz chemisch-synthetischer Pflanzenschutzmittel aber mit Einsatz von Mineraldünger mit konventionellen und ökologischen Anbausystemen an zwei Standorten in Deutschland verglichen werden. Diese Systemversuche sind Teil des Verbundforschungsprojekts "Landwirtschaft 4.0 ohne chemisch-synthetischen Pflanzenschutz (NOcsPS)". Erste Ergebnisse zeigen, dass NOcsPS-Anbausysteme in der Regel geringere Erträge als konventionelle, aber deutlich höhere Erträge als ökologische Anbausysteme erzielen.

Stichwörter

pflanzenschutzmittelfrei, nachhaltige Anbausysteme, Mineraldünger, Gleichstandsaat, Unkrautkontrolle, Bioeffektoren, Agrarökologie

Introduction

In addition to the desired effects, the use of chemical-synthetic plant protection products (CSPs) bears numerous risks for human health and the environment, including biodiversity (Umweltbundesamt, 2023; European Environment Agency, 2023). The current use of pesticides has been recognized as a key driver for biodiversity loss (Chagnon et al., 2015). A rich biodiversity supports many ecosystem services and makes food systems more resilient (Schneider et al., 2023). The reduction of CSPs in EU agriculture is an important lever on the path to more biodiversity and sustainability (European Commission, 2020). In order to achieve the EU's Green Deal target of reducing the use of CSPs by 50% by 2030 and at the same time maintain global food security, further efforts are required in addition to an expansion of organic farming and a reduction in the use of CSPs in conventional agriculture. With regard to global food security in particular, the question arises as to whether, and how, a new farming system managed entirely without CSPs but using mineral fertilizer could be part of the solution. This approach is in line with the European Research Alliance's declaration of intent "Towards a chemical

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Pesticide-free Agriculture". The current discussion on a complete ban on CSPs in protected areas within the framework of the EU's "Sustainable Use Regulation on Pesticide Regulation" (SUR) is also intensifying the search for new farming systems that do not use CSPs. The main challenge in eliminating CSPs from agricultural cropping systems is the maintenance of both yield and quality performance as well as economic viability, since CSP application is an essential pillar for ensuring the yield performance of crops based on high and constant exploitation of their genetic yield potential (Oerke, 2006). For cropping systems without CSPs in Germany, Röder et al. (2021) assume yield reductions compared to conventional systems of 35% for winter wheat, 40% for winter barley, 20% for winter rye, 30% for pea and 15% for maize. Möhring et al. (2021) expect yield reductions of 16–47% depending on the crop for completely CSP-free cropping systems without any adaptation of cultivation measures in Switzerland. For wheat and barley, the expected yield gap is between 20% and 30%, depending on the initial level of yields. Global crop losses due to pests and pathogens are estimated by Savary et al. (2019) at 21.5% for wheat, 22.6% for maize and 21.4% for soybean. Organic cropping systems are generally reported to show a yield gap ranging from about 10% to 60% compared to conventional systems, depending on the crops, location and initial yield level or production intensity (Seufert et al., 2012; Wilbois & Schmidt, 2019; Alvarez, 2021; Zimmermann et al., 2021; Hülsbergen et al., 2023). A wide range of agronomic findings can be taken into account and technical measures taken (Möhring et al., 2021) in order to prevent or reduce yield losses when dispensing with CSPs. While organic farming systems have been well studied, there is little knowledge available on the optimal organization and yield performance of cropping systems when CSPs are dispensed with but mineral fertilizers are applied. In 2019, the NOcsPS research project "Agriculture 4.0 – without chemical-synthetic plant protection but with mineral fertilizers" (Zimmermann et al., 2021) started with the aim of developing and evaluating a sustainable and yield-stable cropping system that dispenses with CSPs while using mineral fertilizers. For this purpose, extensive field trials with different cropping systems were set up at two locations in Germany (the University of Hohenheim (UHOH) in Stuttgart, Baden-Württemberg, and the Julius Kühn Institute in Dahnsdorf (DaD), Brandenburg), and have been running since fall 2019. In these field trials, various cultivation measures are tested for their effect on yield stabilization in a CSP-free cropping system, referred to as "NOcsPS" cropping system in the project and this study. Agroecological cultivation measures, such as the use of diverse crop rotations and plant varieties adapted to the location and cropping system, are intended to enhance biological processes in order to require fewer external resources and improve yield performance. In addition, precision farming technologies are used to improve resource efficiency.

The research hypotheses of this study are that: (1) an optimized combination of agroecological and technical cultivation measures can secure yields in CSP-free cropping systems, and (2) optimized mineral fertilizer use can help improve yield performance of CSP-free cropping systems. The aim of this study is to analyze the yield performance of cropping systems which dispense with CSPs and to compare the yields with conventional and organic cropping systems. In addition to the yield effects, the avoidance of CSPs and the reorientation of cultivation measures in NOcsPS cropping systems such as crop rotation, fertilization, seed patterns, soil cultivation, etc. are expected to have a number of environmental effects. These external effects are currently being analyzed, but are not the subject of this paper. The presented yield analysis is based on data from a to-date 3-year field experiment with typical crop rotations at two locations in Germany. The locations differ in climate and soil properties. Based on first results of the two experimental sites, this study provides an assessment of the implementation of a cropping system without CSPs but with mineral fertilizer.

Material and Methods

Experimental Setup

Experimental sites at University of Hohenheim (UHOH) and Julius Kühn Institute, Dahnsdorf (DaD)

The experimental site of UHOH is located on the Filder-Plateau in Baden-Württemberg, 400 m above sea level. The predominant soil classification is a Stagnic Luvisol (27% clay, 67% silt, 6% sand) on Loess. Soil pH is 7.2 and soil organic carbon was approximately 2% at the start of the experiment. The experimental site is heterogeneous due to water erosion. There is low risk of summer drought. Long-term (1961 to 1990) climatic values (provided by UHOH meteorological weather station) are 697 mm mean annual precipitation and a mean annual temperature of 8.8°C. Annual precipitation in the experimental years was 667 mm in 2020 (lowest April 7 mm, highest February 115 mm), 619 mm in 2021 (lowest January 9 mm, highest June 108 mm) and 717 mm in 2022 (lowest March 22 mm, highest April 104 mm). The mean annual temperature was 10.9 °C in 2020, 10.1 °C in 2021 and 11.7 °C in 2022. These data are based on readings at the Heidfeldhof weather station, UHOH (see supplementary Fig. S1).

The experimental fields of the Julius Kühn Institute are located at DaD, in the Fläming region of Brandenburg, approx. 70 m above sea level. The predominant soil type is classified as a Luvisol, belonging to the Cambisol group (4.6% clay, 35.5% silt, and 57.9% sand), on an end moraine from the Saale Ice Age. The site is characterized by soil heterogeneity and frequent summer drought. Soil pH is 5.8 and soil organic carbon was approximately 1.4% at the start of the experiment. The climatic values for the years 1997 to 2022 (determined by an on-site weather station) were 564 mm mean annual precipitation and a mean annual temperature of 9.6 °C. The annual precipitation in the experimental years was 443 mm in 2020 (lowest in April and November at 6.1 mm, highest in February at 77.6 mm), 545 mm in 2021 (lowest in September at 9.5 mm, highest in July at 92.3 mm) and 392 mm in 2022 (lowest in March at 2.3 mm, highest in August at 68.5 mm). The mean annual temperature was 10.6 °C in 2020, 9.4 °C in 2021 and 10.5 °C in 2022 (see supplementary Fig. S2).

The trials started in 2019 at both locations. Prior to the start of the trials, the experimental areas were cultivated conventionally. Preceding crops were oats at DaD and the respective crops of the crop rotations at UHOH.

Cropping systems

Eight different cropping systems – three conventional, four NOcsPS, and one organic – were created as specific systems, each with an appropriate combination of cultivation measures (Table 1). At the UHOH site, all systems were established; at the DaD site the systems CII, ORG, NOcsPS I, and NOcsPS II were established. The conventional cropping systems differ in terms of 3- and 6-year crop rotations. The four NOcsPS cropping systems differ mainly in seed distribution and fertilization, to analyze the impact of different cultivation measures in CSP-free cropping systems on yield. With regard to seed distribution, normal sowing (NS) is tested against approximate equidistant sowing (aES), which uses different row spacing and seed rates. Fertilization varies between standard application and the placed Cultan technique, supplemented with biostimulants, micronutrients, and algae extracts. Crop rotation differs only slightly in NOcsPS IV. In order to optimize mechanical weed control, the sowing dates for cereals in the NOcsPS cropping systems and the ORG system were set later than in the conventional cropping systems. The seeding rates for the cereal crops in NOcsPS I and NOcsPS IV were therefore increased by about 30% compared to those of the conventional cropping systems. In contrast, aES in NOcsPS II and NOcsPS III led to a reduction in sowing rates of about 20% for technical reasons. Sowing dates and seed rates at DaD and for maize and legumes at UHOH were the same in all systems.

Crop rotations and varieties

Cropping systems differ in crop rotation (Table 2). The conventional systems CI-1 and CI-2 are based on a common typical rotation of three crops (3 phases) (Patterson, 1964) and differ only in the wheat variety to determine its influence. The pesticide-free cropping systems (NOcsPS systems) were designed with an extended diverse 6-year rotation (6 phases) (Patterson, 1964), alternating winter and spring crops and cover crops before maize and soybean, but still focusing on productivity by integrating two wheat phases (sequences) and no non-cash crop (NOcsPS I, II and III). Rye grass was integrated in NOcsPS IV only to help cope with weed infestation. The crop rotation in the organic cropping system (ORG) corresponds to the 6-year rotation in NOcsPS but includes one year of a clover grass mixture instead of spring barley to provide nitrogen. The third conventional system was based on the 6-phase NOcsPS rotation (CII) and implemented as a reference system and to enable comparisons with NOcsPS and ORG. All crop rotations at both sites were accompanied by a legume-free catch-crop mixture, which was sown after harvesting the winter crops and mulched before plowing.

Crop varieties were selected with resistant traits adapted to the site and cropping systems. The wheat varieties were selected with a special focus on their high importance and prevalence in cultivation, as well as good plant resistances, in order to assume a high yield expectation for the NOcsPS systems (RGT Reform, Asory, Achim). For the ORG systems, specific wheat varieties for organic farming were chosen (Govelino, DaD and Philaro, UHOH). Untreated seed was used for the NOcsPS cropping systems and the organic system. For conventionally managed systems, chemically treated seeds were used.

N Fertilization

N fertilizer input for the conventional cropping systems was calculated according to the German Fertilizer Ordinance (“good agricultural practice”, (DÜV, 2017) based on the expected yields. For the determination of fertilization rates for the NOcsPS systems, no established basis could be relied upon, as such systems have not yet been widely adopted in practice. Hence, the fertilization rates here were based on long-term experiences of two trial locations. In the NOcsPS cropping systems in UHOH, nitrogen fertilization of cereals was reduced in line with an 30% lower yield compared to CII. Nitrogen application to maize was reduced by 15% in NOcsPS III only was applied via placement in the root zone. In DaD, the nitrogen fertilizer application for cereals and maize in the

Table 1. Main characteristics of the tested cropping systems in UHOH and DaD. [a] EU standard; [b] including clover grass; [c] approximate equidistant seeding (aES); [d] phase 6 ryegrass instead of spring barley (see Table 2).

		Crop rotation	Seed pattern	CSP application	Mineral fertilizer application
Conventional	CI-1	3-year standard	normal	standard	standard
	CI-2	3-year standard	normal	standard	standard
	CII	6-year NOcsPS adapted	normal	standard	standard
Organic	ORG[a]	6-year NOcsPS adapted[b]	normal	no	no
NOcsPS	NOcsPS I	6-year NOcsPS adapted	normal	no	NOcsPS adapted standard
	NOcsPS II	6-year NOcsPS adapted	aES[c]	no	NOcsPS adapted standard
	NOcsPS III	6-year NOcsPS adapted	aES[c]	no	NOcsPS adapted standard, placed application using Cultan technique, bio-stimulants, micronutrients, zinc, manga-nese and silicon as well as algae extracts
	NOcsPS IV	6-year NOcsPS adapted[d]	normal	no	NOcsPS adapted standard

Table 2: Description of crop rotations and crop varieties of the different cropping systems. [a] In DaD, the systems CII, ORG, NOcsPS I and NOcsPS II are tested. In UHOH, all eight systems are tested; [b] DaD = Dahnsdorf, UHOH = Hohenheim; [c] 1st year. In brackets, abbreviation and crop varieties.

Cropping System (S)[a]	Sites[b]	Phase (P)					
		1	2	3	4	5	6
CI-1	UHOH	Winter wheat (WW1, Asory)	Maize	Soybean			
CI-2	UHOH	Winter wheat (WW2, RGT Reform)	Maize	Soybean			
CII	UHOH	Winter wheat (WW1, Asory)	Maize	Winter triticale	Soybean	Winter wheat (WW2, RGT Reform)	Spring barley
CII	DaD	Winter wheat (WW1, Achim)	Maize	Winter rye	Pea	Winter wheat (WW2, RGT Reform)	Spring barley
ORG	UHOH	Winter wheat (WW1, Philaro)	Maize	Winter triticale	Soybean	Winter wheat (WW2, RGT Reform)	Clover grass
ORG	DaD	Winter wheat (WW1, Achim)	Maize	Winter rye	Pea	Winter wheat (WW2, Govelino)[c] (WW2, RGT Reform)	Clover grass
NOcsPS I	UHOH	Winter wheat (WW1, Asory)	Maize	Winter triticale	Soybean	Winter wheat (WW2, RGT Reform)	Spring barley
NOcsPS I	DaD	Winter wheat (WW1, Achim)	Maize	Winter rye	Pea	Winter wheat (WW2, RGT Reform)	Spring barley
NOcsPS II	UHOH	Winter wheat (WW1, Asory)	Maize	Winter triticale	Soybean	Winter wheat (WW2, RGT Reform)	Spring barley
NOcsPS II	DaD	Winter wheat (WW1, Achim)	Maize	Winter rye	Pea	Winter wheat (WW2, RGT Reform)	Spring barley
NOcsPS III	UHOH	Winter wheat (WW1, Asory)	Maize	Winter triticale	Soybean	Winter wheat (WW2, RGT Reform)	Spring barley
NOcsPS IV	UHOH	Winter wheat (WW1, Asory)	Maize	Winter triticale	Soybean	Winter wheat (WW2, RGT Reform)	Ryegrass

NOcsPS systems was reduced by 30% compared to CII. No N fertilizer was applied to the organic cropping systems.

Winter cereals received N fertilization in all systems, except NOcsPS III, in granular form in two- to threefold split applications at an initial level of 50 kg N/ha. For spring barley and maize, N fertilization was applied once only immediately after sowing. In the NOcsPS III system, all cereals were fertilized with liquid ammonium fertilizer (ASL) in one application using the Cultan technique.

Maize was fertilized with a stabilized solid fertilizer (ammonium sulfate nitrate with DMPP) in one application using a new depot fertilization technique after sowing. The calculation of N fertilization quantities took a conservative approach in order avoid depletion of the stocks and were justified at the time due to site-specific conditions. In the planned second phase of the field trials intends to build on the results achieved so far, and the calculation method will be standardized. The quantities applied were adjusted for the cropping systems and crops. Detailed information on fertilization can be found in the supplementary Tables S1 and S2. In UHOH, a basic fertilization (phosphorus, potassium, sulfur, magnesium and calcium carbonate) was carried out in all systems in 2021 and 2022 according to the assessment of demand.

Plant Protection

Chemical synthetic pesticides (CSPs) were applied in the conventional cropping systems in all years at both sites (UHOH and DaD) according to good agricultural practice. Herbicides were applied in all crops according to requirements and occurrence of weed species. Fungicides were used in the cereal crops and varieties as needed. Growth regulators were applied on a variety-specific basis in wheat and triticale in UHOH and in winter rye in DaD. Insecticides were only necessary in wheat in UHOH and in pea in DaD. As mechanical crop protection, hoeing was performed once or twice to control weeds in all crops in the NOcsPS cropping systems and the ORG system at the UHOH site, according to requirements and trafficability, using an automated camera-controlled hoe. At the DaD site, hoeing was performed only once in maize. As an additional mechanical crop protection measure, a harrow was used at both sites in all crops shortly after sowing and once or twice more until canopy closure. Biological plant protection was carried out at the UHOH site in the NOcsPS III system in the years 2021 and 2022. Biostimulants with microorganisms were applied to the soil once, micronutrients (Mn, Zn and Si) were sprayed onto the plants (leaves) at four different times and algae extracts were applied twice. Trichogramma were applied to maize at both sites in all systems (see supplementary Tables S3 and S4).

Yield measurement

The yields were determined on the basis of plot threshing (plot size UHOH 22.5 m^2 and DaD 27.5 m^2). and are expressed in decitonnes per hectare [dt/ha]. The cereal, soybean and pea yield values refer to a dry matter content of 86% (residual moisture 14%). For silage maize, the total dry matter yield [DM] was determined and converted into dry matter yield per hectare [dt DM/ha].

Experimental design

The two experiments were laid out as strip-plot designs with four replicates (factor name: REP). The description of the design and factors involved follows the nomenclature proposed by Patterson (1964), according to which a rotation is grown in cycles of c years, and the position within a cycle of a rotation, associated with a specific crop, is denoted as a phase. In this study all cropping systems were rotations with cycles of c = 6 years, except for (CI) which had a length of c = 3 years. In the CI system, two variants (CI-1, CI-2) were tested, differing only in the variety of wheat. All other systems had one variant only. This design meant that for each system there were six plots per replicate. In the start year, each phase of a system was allocated to different plots, meaning that all phases are present in each year. The cropping systems (factor name: S) were randomized among the rows (factor name: ROW) within replicates, and the phases (factor name: P) were randomized among the columns (factor name: COL) within replicates. Systems and crops are described in Tables 2 and 1.

Statistical analysis

The experiments were analyzed by linear mixed models using the SAS System. The models used are represented here using symbolic notation described in Patterson (1997) and adapted to repeated measures by Piepho et al. (2004). In addition to the factors described in the section 'Experimental design', we also use the factor C for crops so the crop species grown in a phase (P) of the cropping system (S) can be uniquely identified. We develop the model by first stating the block and treatment models for analysis of a single year. Subsequently, the model is extended to multiple years. The experiments are currently in their first cycle

Single-year analysis

The block model for a single year is (Piepho et al., 2003)

REP/(ROW x COL) = REP + REP.ROW + REP.COL + REP.ROW.COL

All design effects are modelled as random. The treatment model for a single year can be expressed by S.P. To identify the crop (factor name: C) as well as the variety (factor name: V), we expanded this as S.P.C.V. Treatment effects are modelled as fixed. As the rotations involve different crops, it is crucial to check and, where necessary, allow for heterogeneity of variance between crops.

We checked the assumptions of approximate normality and homogeneity of variance using standardized conditional residuals (Stroup et al., 2018). Where necessary, data were transformed and statistical inference performed on the transformed scale. Mean comparisons were conducted by t-tests, and denominator degrees of freedom were adjusted by the Kenward-Roger method. For presentation of results, means are naïvely back-transformed to the original scale. For example, with the logarithmic transformation (base e), the back-transformation is done by exponentiating the adjusted means on the log-scale. These back-transformed means can be interpreted as estimates of medians (Piepho, 2009). For comparison, we also computed the arithmetic means on the original scale.

Across-year analysis

To integrate the data across years (factor name: Y), all terms in the model are expanded (Piepho et al., 2004). The expanded block model is

REP.Y + REP.ROW.Y + REP.COL.Y + REP.ROW.COL.Y

Due to the repeated measures nature of the data, serial correlation must be allowed for all random design effects. Here, we use the autoregressive first-order model, known as AR(1). Using the GLIMMIX procedure of SAS, this is implemented for the row effect as follows:

RANDOM Y/SUBJECT=REP*ROW TYPE=AR(1);

Analogous statements are used for the other random design effects. The treatment model was expanded as follows:

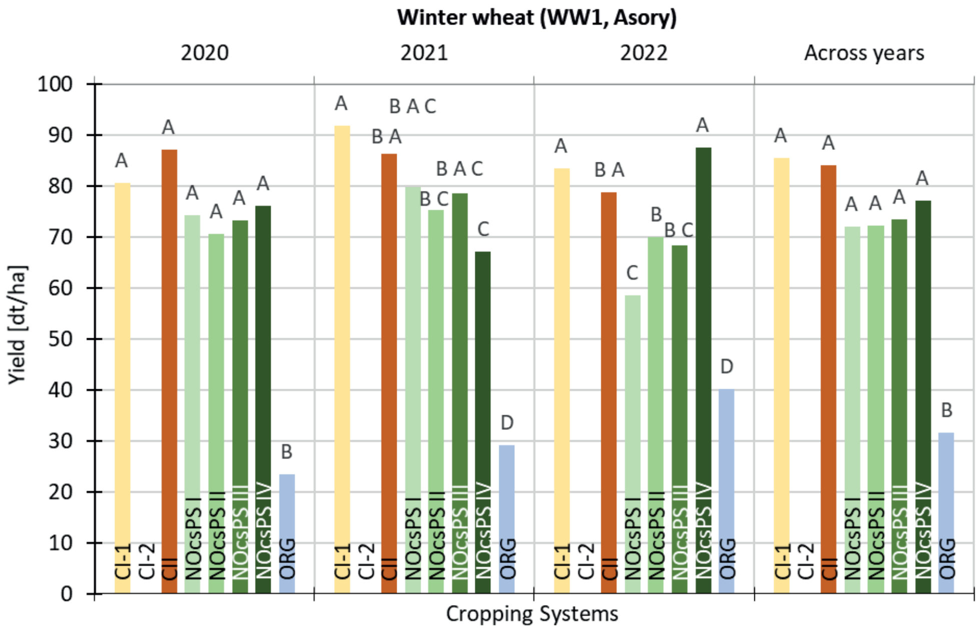
S.P.C.V: Y + S.P.C.V.Y

Year was modelled as a random factor. Hence, the year main effect (Y) and the interaction (S.P.C.V.Y) were modelled as random, whereas the treatment effect S.P.C.V was fixed. In the model statement above, fixed effects are stated before the colon and random effects after the colon. Analysis based on this model was performed analogously to the year-wise analyses.

Results

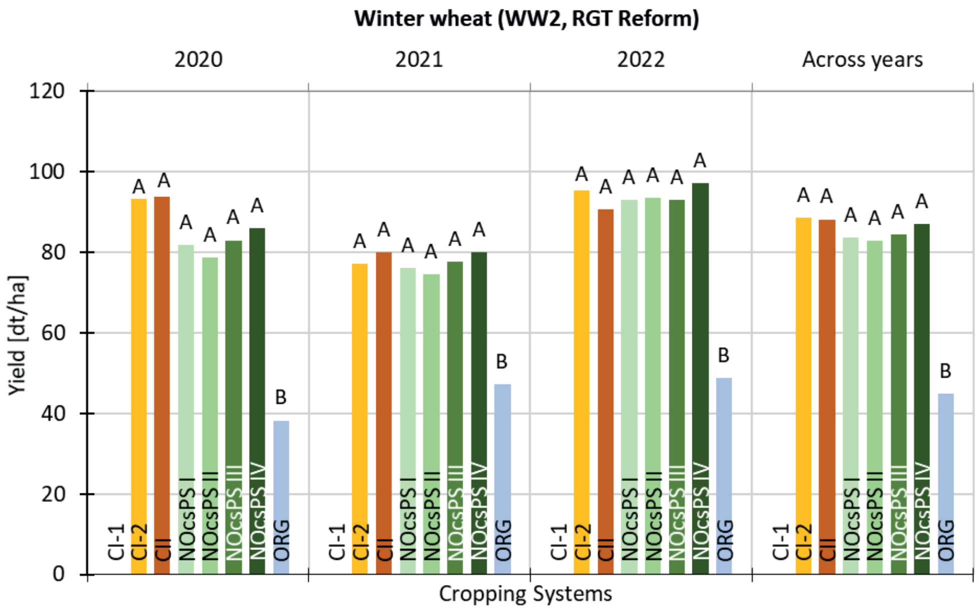
Overall, the NOcsPS field trials show a wide range of yields for the different cropping systems, which also vary greatly between the two locations due to climate and soil conditions, between years due to weather conditions, between the position of crops in the rotation, the varieties used and also through different cultivation measures. Because all phases of the crop rotations are represented in every year, yields for all crops included in all systems (Table 1) can be shown here for the years 2020 to 2022.

Wheat yields were generally higher in UHOH (Fig. 1 and Fig. 2) than in DaD (Fig. 3 and Fig. 4) except in 2020 and the organic systems, which can be attributed to the more



Yield difference [%] to CII	CI-1	CI-2	CII	NOcsPS I	NOcsPS II	NOcsPS III	NOcsPS IV	ORG
2020	-8^{A}	-	Reference	-15^{A}	-19^{A}	-16^{A}	-13^{A}	-73^{B}
2021	7^{A}	-	Reference	-7^{BA}	-13^{B}	-9^{BA}	-22^{B}	-66^{C}
2022	6^{A}	-	Reference	-26^{C}	-11^{B}	-13^{BC}	11^{A}	-49^{D}
Difference across years [%]	**2^{A}**	**-**	**Reference**	**-14^{A}**	**-14^{A}**	**-13^{A}**	**-8^{A}**	**-62^{B}**

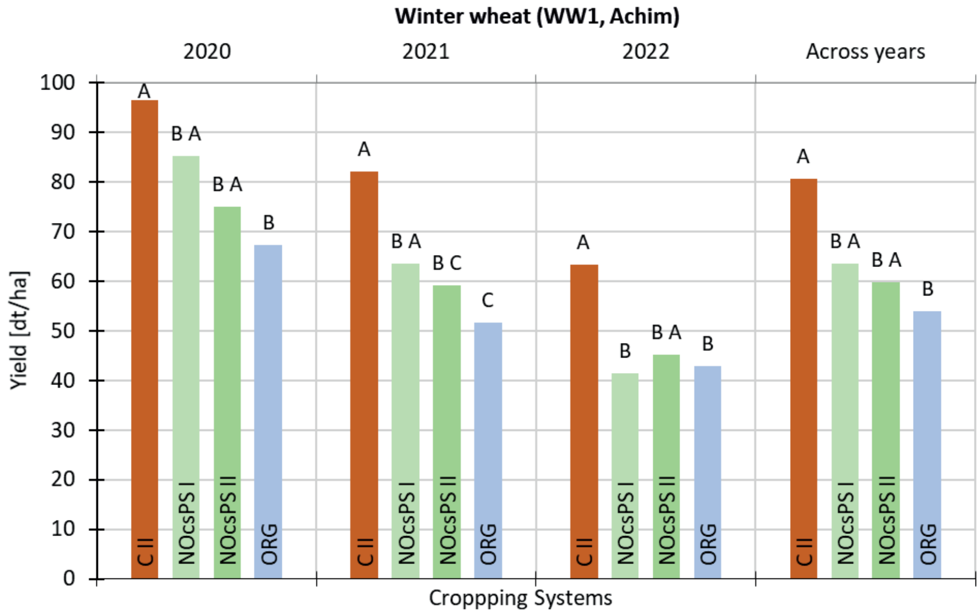
Fig. 1. Winter wheat yields (WW1, Asory) [dt/ha] in UHOH. Systems that do not share a letter differ significantly ($p<0.05$). Table: Yield difference [%] in comparison to reference system CII and difference across years [%] based on three-year yield average.



Yield difference [%] to CII	CI-1	CI-2	CII	NOcsPS I	NOcsPS II	NOcsPS III	NOcsPS IV	ORG
2020		-1^{A}	Reference	-13^{A}	-16^{A}	-12^{A}	-8^{A}	-59^{B}
2021		-4^{A}	Reference	-5^{A}	-7^{A}	-3^{A}	0^{A}	-41^{B}
2022		5^{A}	Reference	3^{A}	3^{A}	2^{A}	7^{A}	-46^{B}
Difference across years [%]		**0^{A}**	**Reference**	**-5^{A}**	**-6^{A}**	**-4^{A}**	**-1^{A}**	**-49^{B}**

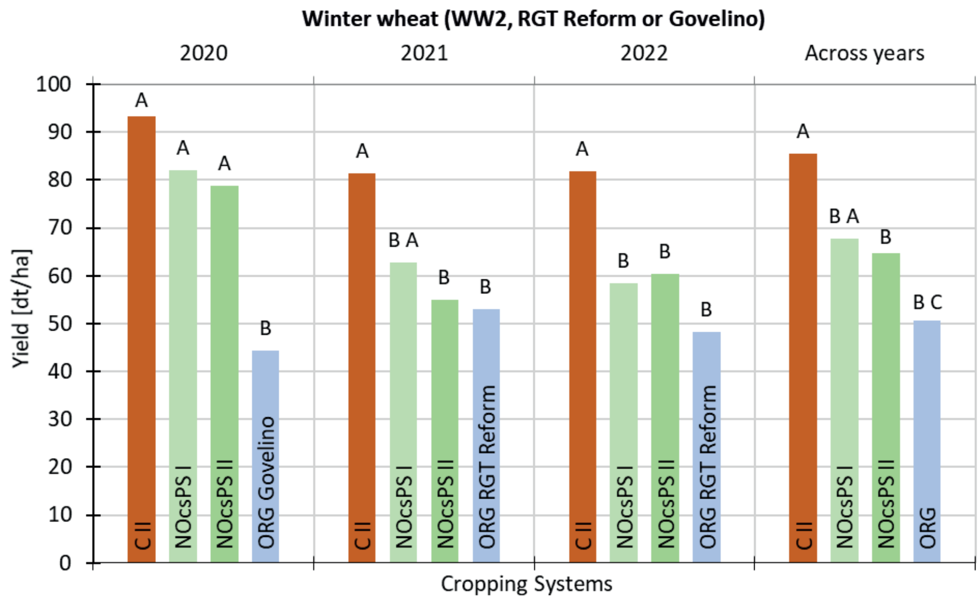
Fig. 2. Winter wheat yields (WW2, RGT Reform) [dt/ha] in UHOH. Systems that do not share a letter differ significantly ($p<0.05$). Table: Yield Difference [%] in comparison to reference system CII and difference across years [%] based on three-year yield average.

favourable weather and soil conditions. In the conventional and NOcsPS systems, yields of winter wheat 2 (WW2) were higher and more stable over time than those of winter wheat 1 (WW1) at both sites. This can be attributed to the different varieties in WW1 (UHOH: Asory, DaD: Achim) and WW2 (UHOH/DaD: RGT-Reform) or the more favorable preceding crops in WW2, namely soybean (UHOH) and peas (DaD) instead of spring barley in WW1. Across years, in UHOH, CI performed slightly better than CII, but not significantly. CII yields ranged from 79 to 87 dt/ha in WW1 and 80 to 94 dt/ha in WW2. Across years, the average wheat yields of the different NOcsPS systems were not significantly different from CII and ranged between 72 and 77 dt/ha (8–14% below CII) in WW1 and between 83 and 87 dt/ha (1–6% below



Yield difference [%] to CII	CII	NOcsPS I	NOcsPS II	ORG
2020	Reference	-12 ^{A}	-22 ^{A}	-30 ^{A}
2021	Reference	-23 ^{A}	-28 ^{BA}	-37 ^{B}
2022	Reference	-35 ^{A}	-29 ^{A}	-32 ^{A}
Difference across years [%]	**Reference**	**-21** ^{A}	**-26** ^{A}	**-33** ^{A}

Fig. 3. Winter wheat yields (WW1, Achim) [dt/ha] in DaD. Systems that do not share a letter differ significantly ($p<0.05$). Table: Yield difference [%] in comparison to reference system CII and difference across years [%] based on three-year yield average.



Yield difference [%] to CII	CII	NOcsPS I	NOcsPS II	ORG
2020	Reference	-12 ^{A}	-16 ^{A}	-53 ^{B}
2021	Reference	-23 ^{A}	-32 ^{A}	-35 ^{A}
2022	Reference	-29 ^{A}	-26 ^{A}	-41 ^{A}
Difference across years [%]	**Reference**	**-21** ^{A}	**-24** ^{A}	**-41** ^{BA}

Fig. 4. Winter wheat yields (WW2, RGT Reform or Govelino) [dt/ha] in DaD. Systems that do not share a letter differ significantly ($p<0.05$). Table: Yield difference [%] in comparison to reference system CII and difference across years [%] based on three-year yield average.

CII) in WW2. In NOcsPS, wheat yields were not significantly different from CII in almost all years and systems, but significantly different from ORG. Within the NOcsPS systems, NOcsPS III and IV appear to perform slightly better than NOcsPS I and II, possibly due to additional micro-nutrients and the rye grass phase. Across years, wheat yields differed significantly between CII and ORG. The yield differences of 62% in WW1 and 49% in WW2 were higher in UHOH than in DaD for reasons explained in the discussion.

Wheat yields were lower in DaD than in UHOH in almost all systems and years, with the exception of the organic system. Due to the increasing drought over the three years, there was a tendency for yields in DaD to decrease from 2020 to 2022, especially in WW1 (Fig. 3). Compared to WW1, the yields of WW2 were more stable across years and on average slightly higher (Fig. 4). For both WW1 and WW2, CII was superior in yield to all other systems except the organic system in all years of the trial. Across years and systems, NOcsPS wheat yields were 12-35% lower than CII yields in WW1 and 12–32% in WW2. Across years, the yield gap of WW1 and WW2 in relation to CII was 21% for NOcsPS I and 26% for NOcsPS II. With the sole exception of NOcsPS I in 2022 (WW1), all NOcsPS systems at DaD were superior to ORG in terms of wheat yield. In all years, ORG wheat yields were significantly lower than CII yields. The yield difference between ORG and CII was greater in WW2 (41%) than in WW1 (33%), possibly due to differences in the varieties used or the preceding crops. While wheat yields in the CII system (WW1 and WW2) in DaD differed significantly from yields in the organic systems, no clear trend was observed for the NOcsPS systems. Across years, in WW1, NOcsPS yields are not significantly different from CII and ORG, in WW2, there is only a significant difference between NOcsPS II s and ORG.

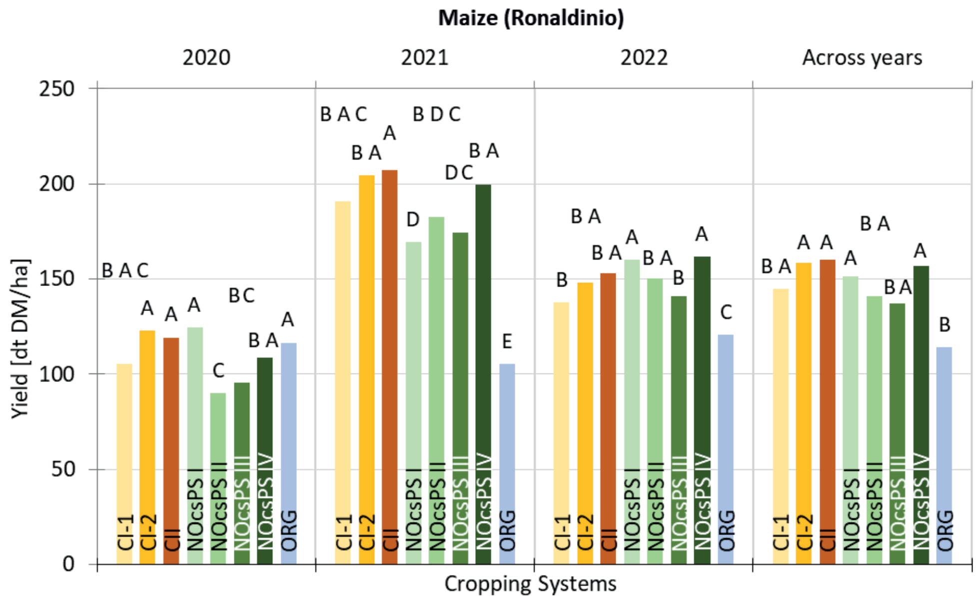
The results for maize in UHOH show no significant differences in yield across years between the NOcsPS systems and the reference system CII (Fig. 5). Within the NOcsPS systems, NOcsPS I and IV performed the best. Over the years, maize yields in NOcsPS I and IV were not significantly lower than in CI and CII, but significantly higher than in ORG. Across the years, the yield gap between the NOcsPS systems and CII ranged between 2% and 14%.

Maize yields in DaD (Fig. 6) suffered greatly from drought in all years, resulting in lower yields than in UHOH. Especially the dry Spring in 2020, which slowed down crop establishment, led to the lowest maize yields in the first year. Interestingly, in the organic system the maize yields in 2020 were the same as in all other years. In DaD, CII was significantly superior to all other systems over the entire period, with the exception of NOcsPS I and ORG in 2021. Across years, NOcsPS and ORG yields are significantly lower compared to CII with a yield gap of 31% for NOcsPS I, 56% for NOcsPS II and 32% for ORG. Reasons for that are drought, nutrient deficiency and aES problems.

In triticale, which was planted in UHOH instead of rye, the yield results are very similar to those of rye in DaD. In all years, CII achieved the highest grain yields (Fig. 7). The NOcsPS systems did not differ significantly from each other in grain yield in all years. Compared to CII, NOcsPS yields were not significantly lower across years, but, the ORG system had significantly lower yields than all other systems in all years.

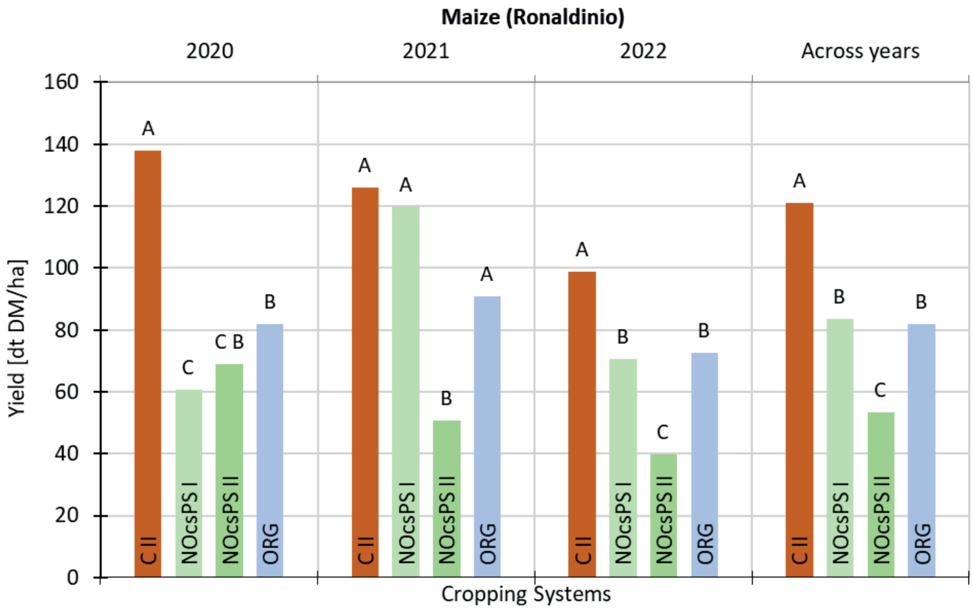
In DaD, winter rye proved to be a robust crop, well adapted to the site conditions. It showed lower yield depression though drought than wheat over the trial years (Fig. 8). The NOcsPS systems also performed well with non-significant yield differences to CII of 13 and 20% across years. Both NOcsPS systems tended to be higher-yielding than the organic system in all trial years. In 2022 and across years, this effect was also confirmed statistically. Rye yields in ORG were significantly lower (27–57%) than CII in all years.

Soybean yields in UHOH show strong fluctuations between systems and years (Fig. 9). In 2020 and 2022, yields were far below the expected level in all systems. The low yields in 2020 can be partly explained by the spring drought, which affected crop establishment after sowing, but also by bird damage and weed infestation. Across years, all systems achieved similar, non-significantly different yield levels. Within the NOcsPS systems, NOcsPS I and NOcsPS IV performed best, with equal or higher yields than CII, while NOcsPS II and III suffered from weeds and bird damage due to the row spacing. In 2021, only the conventional systems and NOcsPS II showed non-significant yield differences. In 2022, NOcsPS I performed best.



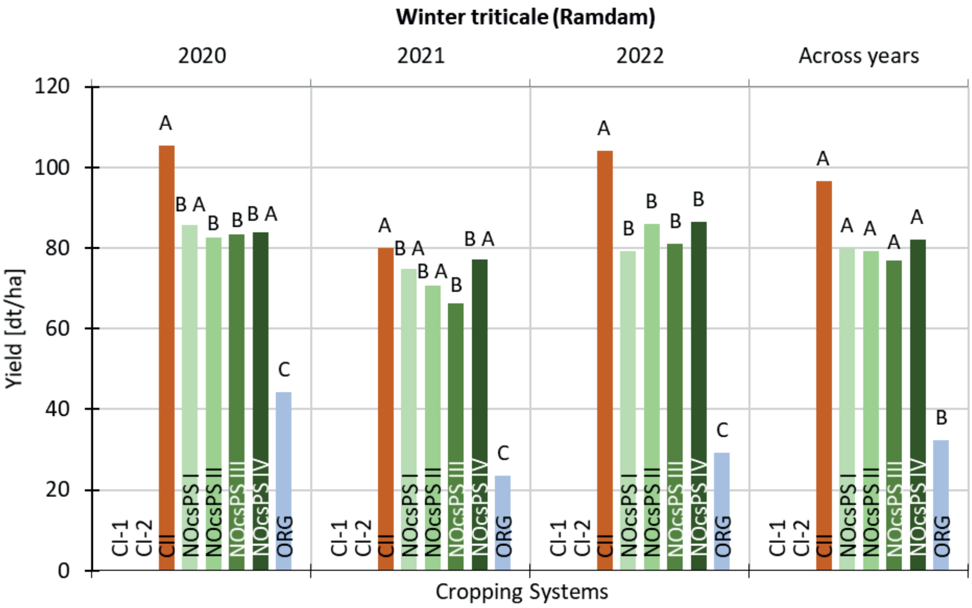
Yield difference [%] to CII	CI-1	CI-2	CII	NOcsPS I	NOcsPS II	NOcsPS III	NOcsPS IV	ORG
2020	-12^{BAC}	3^{A}	Reference	4^{A}	-24^{C}	-20^{BC}	-9^{BA}	-2^{A}
2021	-8^{AB}	-2^{A}	Reference	-18^{C}	-12^{BAC}	-16^{BC}	-4^{A}	-49^{D}
2022	-10^{B}	-3^{BA}	Reference	4^{A}	-2^{BA}	-8^{B}	6^{A}	-21^{C}
Difference across years [%]	**-10^{BA}**	**-1^{A}**	**Reference**	**-5^{A}**	**-12^{BA}**	**-14^{BA}**	**-2^{A}**	**-29^{B}**

Fig. 5. Maize yields (Ronaldinio) [dt DM/ha] in UHOH. Systems that do not share a letter differ significantly ($p<0.05$). Table: Yield difference [%] in comparison to reference system CII and difference across years [%] based on three-year yield average.



Yield difference [%] to CII	CII	NOcsPS I	NOcsPS II	ORG
2020	Reference	-56^{B}	-50^{BA}	-41^{A}
2021	Reference	-5^{A}	-60^{B}	-28^{A}
2022	Reference	-29^{A}	-60^{B}	-27^{A}
Difference across years [%]	**Reference**	**-31^{A}**	**-56^{B}**	**-32^{A}**

Fig. 6. Maize yields (Ronaldinio) [dt DM/ha] in DaD. Systems that do not share a letter differ significantly (p<0.05). Table: Yield difference [%] in comparison to reference system CII and difference across years [%] based on three-year yield average.

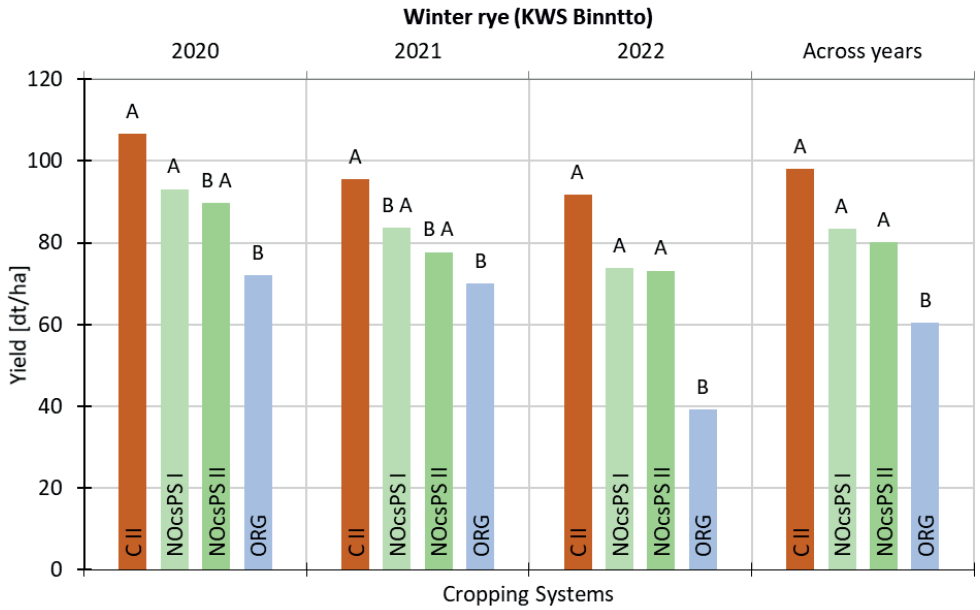


Yield difference [%] to CII	CI-1	CI-2	CII	NOcsPS I	NOcsPS II	NOcsPS III	NOcsPS IV	ORG
2020	-	-	Reference	-19^{A}	-22^{A}	-21^{A}	-20^{A}	-58^{B}
2021	-	-	Reference	-6^{A}	-11^{A}	-17^{A}	-4^{A}	-70^{B}
2022	-	-	Reference	-24^{A}	-17^{A}	-22^{A}	-17^{A}	-72^{B}
Difference across years [%]	**-**	**-**	**Reference**	**-17^{A}**	**-18^{A}**	**-20^{A}**	**-15^{A}**	**-66^{B}**

Fig. 7. Winter triticale yields (Ramdam) [dt/ha] in UHOH. Systems that do not share a letter differ significantly (p<0.05). Table: Yield Difference [%] in comparison to reference system CII and difference across years [%] based on three-year yield average.

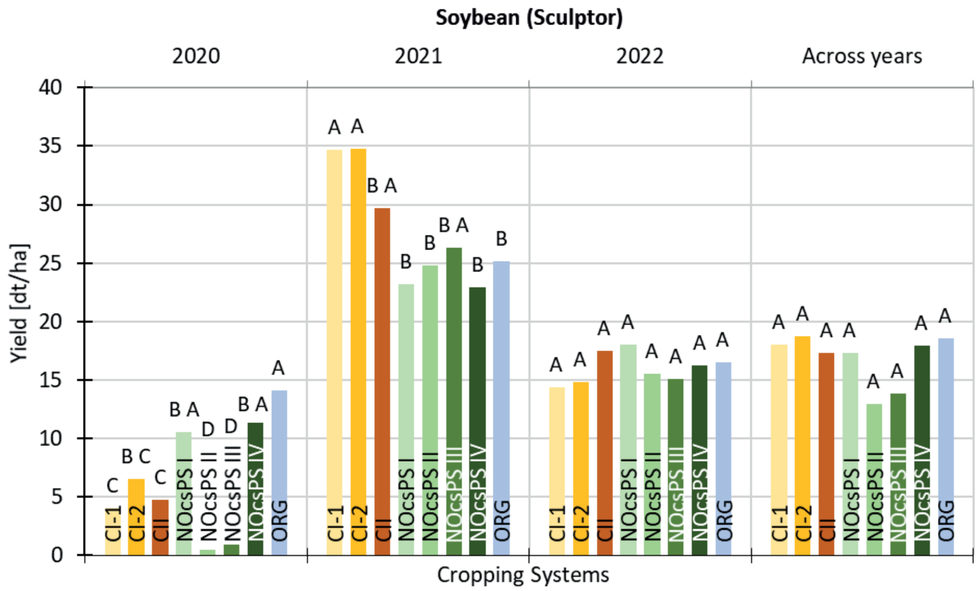
Pea yields in DaD fluctuated widely in all systems (Fig. 10). In 2020, yields were still good (except in the NOcsPS II system), but considerably lower in the following two trial years due to dry weather conditions. Across years, pea yields in ORG and NOcsPS I were very competitive with conventional systems and did not differ significantly from CII, whereas NOcsPS II yields were significantly lower because of aES problems.

Spring barley yields were approximately twice as high in UHOH (Fig. 11) as in DaD (Fig. 12), where frequent droughts occurred in early summer. In UHOH, spring barley was most productive in CII in all years, but yield losses in NOcsPS systems across years (16% to 19%) were not significant. Significant yield differences occurred between the conventional and NOcsPS variants in 2021 and 2022. Yields did not differ significantly between the different NOcsPS systems.



Yield difference [%] to CII	CII	NOcsPS I	NOcsPS II	ORG
2020	Reference	-13^{A}	-16^{BA}	-33^{B}
2021	Reference	-12^{A}	-19^{A}	-27^{A}
2022	Reference	-20^{A}	-20^{A}	-57^{B}
Difference across years [%]	**Reference**	**-15^{A}**	**-18^{A}**	**-38^{B}**

Fig. 8. Winter rye yields (KWS Binntto) [dt/ha] in DaD. Systems that do not share a letter differ significantly ($p<0.05$). Table: Yield Difference [%] in comparison to reference system CII and difference across years [%] based on three-year yield average.

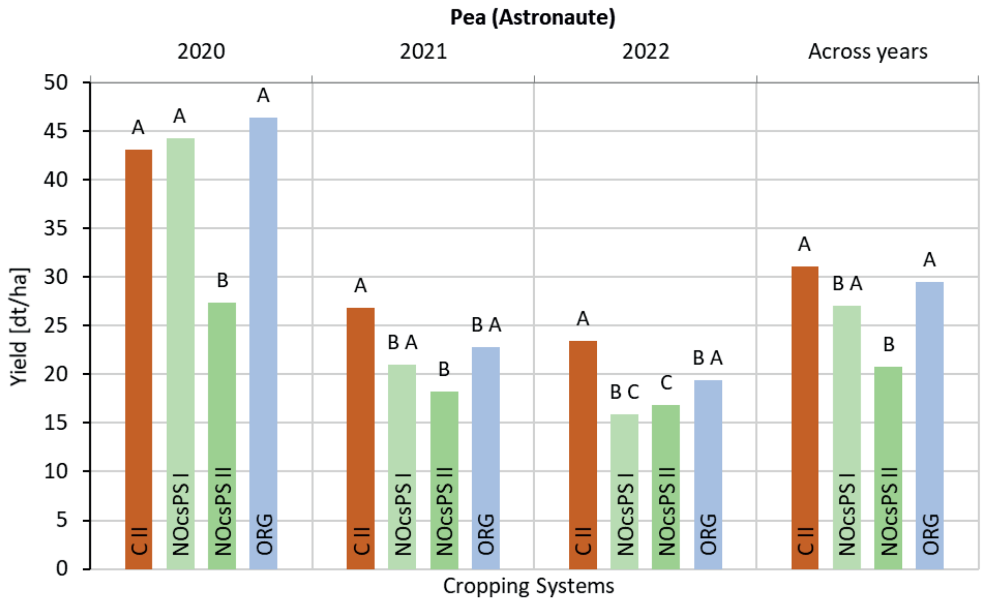


Yield difference [%] to CII	CI-1	CI-2	CII	NOcsPS I	NOcsPS II	NOcsPS III	NOcsPS IV	ORG
2020	-15^{C}	38^{BC}	Reference	121^{BA}	-90^{D}	-80^{D}	139^{BA}	196^{A}
2021	17^{A}	17^{A}	Reference	-22^{B}	-17^{B}	-11^{BA}	-23^{B}	-15^{B}
2022	-18^{A}	-15^{A}	Reference	3^{A}	-11^{A}	-14^{A}	-7^{A}	-6^{A}
Difference across years [%]	**4^{A}**	**8^{A}**	**Reference**	**0^{A}**	**-25^{A}**	**-20^{A}**	**4^{A}**	**8^{A}**

Fig. 9. Soybeans yields (Sculptor) [dt/ha] in UHOH. Systems that do not share a letter differ significantly ($p<0.05$). Table: Yield Difference [%] in comparison to reference system CII and difference across years [%] based on three-year yield average.

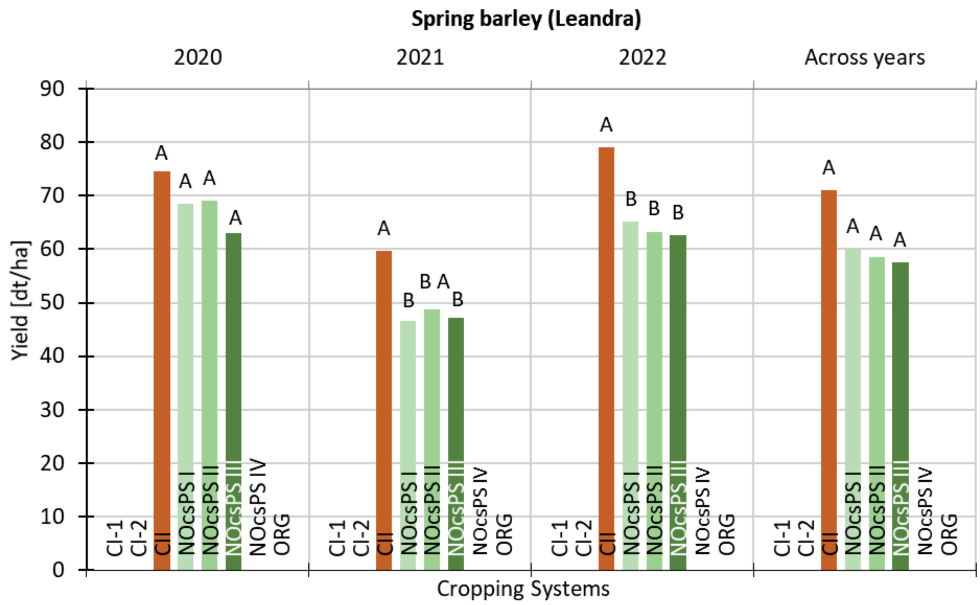
Spring barley yields in DaD show a similar picture to those in UHOH, only at a lower level (Fig. 12). Across years, the yield difference of the NOcsPS I system to CII is not significant and, at 19%, similar to that of the NOcsPS systems in UHOH. NOcsPS I performed better than NOcsPS II with aES in all years. Across years, the yield of NOcsPS II is significantly lower (almost 40%) than CII.

Table 3 shows the average percentage yield differences of the different crops and cropping systems in UHOH and DaD compared to the CII system for the years 2020 to 2022. The results of the three-year field trials show that wheat yields of the NOcsPS systems were on average 4 to 12% lower than conventional wheat yields in UHOH and 23 to 24% lower in DaD, while organic wheat yields were 33 to 62% lower than CII, depending on location. For the other cereals, such as winter triticale, winter rye and spring barley, the yield difference compared to CII ranged between 17% and 29% for the average of the NOcsPS systems, and between 38 and 66% for the organic systems. For legumes as well as for maize in DaD,



Yield difference [%] to CII	CII	NOcsPS I	NOcsPS II	ORG
2020	Reference	3^{A}	-37^{B}	8^{A}
2021	Reference	-22^{A}	-32^{A}	-15^{A}
2022	Reference	-32^{BA}	-28^{B}	-17^{A}
Difference across years [%]	**Reference**	**-13^{BA}**	**-33^{B}**	**-5^{A}**

Fig. 10. Pea yields (Astronaute) [dt/ha] in DaD. Systems that do not share a letter differ significantly ($p<0.05$). Table: Yield difference [%] in comparison to reference system CII and difference across years [%] based on three-year yield average.



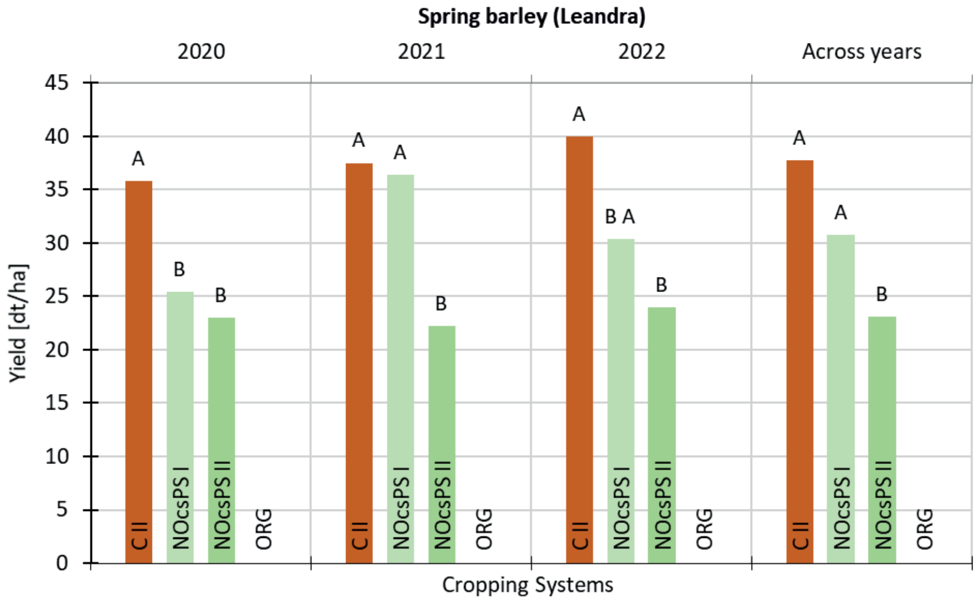
Yield difference [%] to CII	CI-1	CI-2	CII	NOcsPS I	NOcsPS II	NOcsPS III	NOcsPS IV	ORG
2020			Reference	-8^{A}	-8^{A}	-16^{A}		
2021			Reference	-22^{A}	-18^{A}	-21^{A}		
2022			Reference	-17^{A}	-20^{A}	-21^{A}		
Difference across years [%]			**Reference**	**-15^{A}**	**-18^{A}**	**-19^{A}**		

Fig. 11. Spring barley yields (Leandra) [dt/ha] in UHOH. Systems that do not share a letter differ significantly ($p<0.05$). Table: Yield difference [%] in comparison to reference system CII and difference across years [%] based on three-year yield average.

the organic system performed better than the average of the NOcsPS systems.

Discussion

The objective of this study is a comparison of different agricultural systems with the focus on a new farming system without application of CSPs but with mineral fertilizer. Based on yield as an indicator for the productivity, NOcsPS cropping systems were compared with a conventional and an organic managed cropping system over a period of three years. For this purpose the experimental design of the field trials was set up for a system comparison rather than for a factorial approach (see e.g. Drinkwater et al., 2016). For example, the amount of nitrogen fertilization was adapted according to yield expectations and crop demand in the specific systems, resulting in different levels as well as formulations of N fertilizers. In addition, appropriate crop varieties



Yield difference [%] to CII	CII	NOcsPS I	NOcsPS II	ORG
2020	Reference	-29[A]	-36[A]	-
2021	Reference	-3 [A]	-41[B]	-
2022	Reference	-24[A]	-40[A]	-
Difference across years [%]	**Reference**	**-19**[A]	**-39** [B]	-

Fig. 12. Spring barley yields (Leandra) [dt/ha] in DaD. Systems that do not share a letter differ significantly ($p<0.05$). Table: Yield difference [%] in comparison to reference system CII and difference across years [%] based on three-year yield average.

Table 3. Yield difference across years [%] of the different cropping systems in comparison to the reference systems CII in UHOH and DaD, based on the three-year yield average (2020-2022). The abbreviation n.a. indicates that the systems NOcsPS III and NOcsPS IV were not tested in DaD.

Crops	Site	NOcsPS I	NOcsPS II	NOcsPS III	NOcsPS IV	NOcsPS average	ORG
Winter wheat (WW1)	UHOH	-14	-14	-13	-8	**-12**	**-62**
Winter wheat (WW2)	UHOH	-5	-6	-4	-1	**-4**	**-49**
Winter wheat (WW1)	DaD	-21	-26	n.a.	n.a.	**-24**	**-33**
Winter wheat (WW2)	DaD	-21	-24	n.a.	n.a.	**-23**	**-41**
Maize	UHOH	-5	-12	-14	-2	**-8**	**-29**
Maize	DaD	-31	-56	n.a.	n.a.	**-43**	**-32**
Winter triticale	UHOH	-17	-18	-20	-15	**-18**	**-66**
Winter rye	DaD	-15	-18	n.a.	n.a.	**-16**	**-38**
Soybean	UHOH	0	-25	-20	4	**-10**	**8**
Peas	DaD	-13	-33	n.a.	n.a.	**-23**	**-5**
Spring barley	UHOH	-15	-18	-19	n.a.	**-17**	**n.a.**
Spring barley	DaD	-19	-39	n.a.	n.a.	**-29**	**n.a.**

were chosen for conventional as well as organic cropping systems. For the comparison of yield results, it has to be taken into account that the organic system chosen here relies fully on nitrogen supply from microbial N fixation by legumes in the crop rotation. This choice corresponds to the research hypothesis in this study that optimized mineral fertilizer use can help improve yield performance of CSP-free cropping systems.

The following sections discuss the yield performance of different systems as affected by site factors in interaction with specific management practices.

Yield performance as influenced by system effects

As was to be expected, the yield performance of most crops apart from legumes was lowest in the organic systems. In line with the findings of Hülsbergen et al. (2023), wheat yields in UHOH were 50-60% lower in the organic system than in the conventional systems. The lower nitrogen supply – and thus deficiency – is the major reason for this difference. This was even more pronounced in 2020 in UHOH.

This can be observed, for example, by analyzing the significantly higher yields in the ORG system in 2020 at DaD compared to UHOH. One possible explanation could be the different preceding crops in the field trials, which may have resulted in a lower nutrient stock in UHOH at the beginning of the field trials. An indication of this is provided by the low Nmin values observed in UHOH (see supplementary Table S1), which suggests that the fertilization strategy needs to be reconsidered.

Since the ORG system was assumed to be part of an arable farm without livestock and organic fertilizer, nitrogen (N) was only supplied through a clover-grass mixture and catch crops as part of the crop rotation. This source of nutrients does not seem to be sufficient to provide the plants with enough nutrients for a good and stable yield performance over time. The N deficiency is particularly evident in the yield of winter rye in the third year of the trial at DaD, which is probably due to the high N uptake of the preceding crops wheat and maize. To address nutrient deficiencies in the ORG systems in future, improved N supply strategies would have to be considered.

It can thus be concluded that the use of mineral fertilizer in all NOcsPS systems is the major measure that makes its yield performance superior to organic systems. Part of the tendentially lower yields of NOcsPS may also be explained by the effect of a lower N supply of about 30% compared to the conventional system, which was applied as part of the systems approach taken here and the assumption of lower yields in the NOcsPS systems. Only maize at UHOH received the same amount of N mineral fertilizer in the NOcsPS system as in the conventional system and indeed no yield differences were found for maize between these two systems across years (see Fig. 5).

In addition to the lower N supply, dispensing with CSP application is another factor that leads to lower yields in the NOcsPS compared to the conventional systems. Möhring et al. (2021) show in their study that yield reductions of 20% can be expected for cereals at a medium yield level when CSPs is not used and fertilization is reduced. Effects of non-using CSPs and fertilizer reduction can hardly be separated. Röder et al. (2021) mention yield reductions of 35 to 40% in winter cereals when CSPs is dispensed with but fertilizer input is not reduced. For legumes, a 30% yield reduction is to be expected, but for maize only 15% (Röder et al., 2021). Compared to these yield losses reported for CSP-free cropping systems, the yield differences between the NOcsPS and conventional systems in our field trials (Table 3) are in part smaller. This underlines the importance and potential of an optimal, site-specific combination of management practices for the successful implementation of CSP-free cropping systems.

While yields in DaD decreased over the years in almost all systems and crops, yields those in UHOH remained more stable over the years. This could be due to the impact of site characteristics. The soil in DaD has a low water-holding capacity on account of its high sand content. This was compounded by the low rainfall during the growing season. As a result, nutrient uptake was constrained and plant growth inhibited. It is possible that this effect was further intensified by reduced nitrogen fertilization in the NOcsPS cropping systems, which may have resulted in nitrogen deficiency. By contrast, the predominant loess soil present at UHOH has a higher water-holding capacity and significantly better nutrient availability. This is reflected in the yields of the winter wheat variety RGT Reform in UHOH, which remained at a similarly high level across all years and systems, with no statistically significant differences between the NOcsPS and the conventional system CII.

Another relevant factor that may affect yield performance is the choice of varieties, which differ between the NOcsPS systems and the ORG system. The lower yield performance of organic wheat in UHOH compared to DaD indicates that standard wheat varieties can also be beneficial in organic systems. While in UHOH, Philaro is used as a typical variety in organic farming in the ORG system, in DaD the standard wheat varieties Achim and RGT Reform were used in all systems because of the disappointingly low performance of the organic variety Govelino in the first year. Indeed, the relative performance of wheat in the organic system was better when these standard varieties were used (see Fig. 4).

Yields were higher in the NOcsPS I system than in the NOcsPS II system for all crops, and at UHOH NOcsPS IV performed better than NOcsPS III. The main difference between these systems is that the better performing NOcsPS I and IV systems used standard mineral fertilizer applications and normal seeding procedures, whereas the NOcsPS II and III systems used Cultan application techniques and/or approximate equidistant seeding (aES). The following two sections discuss the effects of Cultan and seeding techniques and the effects of omitting CSPs application, using the example of weed control.

Cultan technique

Weather conditions and crop variety selection have been indicated as factors having a strong influence on yields when the Cultan technique is used. This was determined in three-year trials with winter wheat varieties using the Cultan technique with one application of urea ammonium sulfate solution versus two applications of urea or calcium ammonium nitrate (Hermann et al., 2007; Weber et al., 2008). In our study, the Cultan technique was applied for fertilization in UHOH in the NOcsPS III system and was expected to have a positive effect on yields. However, the results obtained did not confirm these expected effects. When comparing NOcsPS II and NOcsPS III, no positive effect was found through optimized fertilization except for wheat, which had slightly higher yields than in the NOcsPS I and NOcsPS II systems. This could be an effect of the biostimulants, micronutrients, silicon and algae extract applied. Silicon (Si), manganese (Mn) and zinc (Zn) can enhance the plants' tolerance to abiotic and biotic stress factors (Imran et al., 2013; Bradáčová et al., 2016; Moradtalab et al., 2018; Weinmann & Neumann, 2020).

Approximate equidistant seeding (aES)

Equidistant seeding encourages an earlier crop closure and may have advantages in weed suppression (Weiner et al., 2001; Olsen et al., 2012). Olsen et al. (2012) found the lowest weed biomass at a high seeding rate and uniform plant stand distribution. Lu et al. (2020), in contrast, showed that seeding density has less influence on weed pressure, but optimizing spatial distribution can usually increase yield and weed suppression, especially in the world's major crops maize, wheat, and soybean. The presented results from UHOH and DaD field trials did not confirm these desired effects so far. Particularly striking was the low yield for maize in the NOcsPS II system at DaD site in 2020 and also in the subsequent years. This is probably due to the mechanical weed control, which is difficult to implement in a narrow row distance (37.5 cm). Another reason for the yield reductions in the two NOcsPS systems with aES could be the reduced seed rate associated with aES in conjunction with the later sowing date in NOcsPS systems, because the two measures are not compatible. In winter cereals NOcsPS cropping systems require later sowing dates to reduce weed pressure, and higher seed rates to compensate for the potentially reduced tiller production due to later sowing. An early sowing date can favour the development of plants (Spink et al., 2000). Accordingly, it must be assumed that the seed rate and seeding date were not suitable for NOcsPS II and NOcsPS III cropping systems, hence the lowest yields were recorded in these systems at both locations.

Weed control

Dispensing with CSPs in NOcsPS cropping systems rules out the use of herbicides. For this reason, a camera-controlled hoe was used for weed control. Studies confirm that precise inter-row hoeing with automated sensor systems effectively reduces weeds (Gerhards et al., 2020; Saile et al., 2023), and this was also verified in our experiment (data not shown). However, it is to be expected that the effects of herbicide avoidance will become apparent after a certain period (Schwarz & Moll, 2010; Schwarz & Pallutt, 2016; Schwarz, 2020), and weed pressure in NOcsPS cropping systems is likely to be higher compared to conventional systems. Furthermore, it is likely that with continued, steady-state management, as envisaged in NOcsPS cropping systems and even organic farming systems, perennial weeds such as *Cirsium arvense* (L.) to control and become more established.

Weed pressure can also be managed by wide crop rotation with competitive crops (Cornelius & Bradley, 2017; Liu et al., 2022). For this reason, crop rotation with appropriate crops and crop varieties is an essential aspect of NOcsPS cropping systems. This becomes evident at the UHOH site in the NOcsPS IV cropping system, where ryegrass was used in the crop rotation instead of spring barley. It has been confirmed that cover crops such as ryegrass can be used as a phytosanitary measure to mitigate weed pressure (Cornelius & Bradley, 2017; Liu et al., 2022; Seefeldt et al., 2023; Trolove et al., 2023). However, it should also be mentioned that ryegrass requires timed management practices and should be mowed before flowering to prevent seed pressure in the area, which could in turn lead to ryegrass growth in the following crop (Reeves & Smith, 1975). In our trial, it was assumed that weed suppression by ryegrass benefits the following crop, winter wheat (Asory), as indicated by the better yield results of the NOcsPS IV system in the 3-year average of 2020 to 2022 compared to the yields of the winter wheat variety Asory in the other NOcsPS cropping systems. This result suggests that the position of a crop in the crop rotation is important for an efficient and sustainable NOcsPS cropping system, and that the preceding crop also plays a crucial role. This was confirmed by the legume soybean as a preceding crop to the winter wheat variety RGT Reform (WW2) at the UHOH site. However, it was not confirmed for the legume pea at the DaD site for the same winter wheat variety. The reason for this could be the predominant drought during 2021 and 2022, which may have hampered the N-fixation by pea.

Conclusion

The comparison of novel cropping systems, that are run without the use of chemical-synthetic crop protection products but with mineral fertilizer use (NOcsPS), with conventional and organic cropping systems, revealed a high potential for the transformation to crop production systems that do not apply CSPs.

In three-year field trials at two contrasting locations, it was shown that yields in NOcsPS systems can be maintained at a stable level through the use of mineral fertilizers and mechanical weed control. This is at least the case under the condition of favorable weather and only moderate diseases and pest infestation. In terms of crop yield, the reliable supply of nitrogen through mineral fertilizer is a major advantage of the NOcsPS system over organic cropping systems.

The expected benefits of aES on weed control through optimized plant distribution in NOcsPS systems could not be confirmed. In addition, the strategies for slow-release nitrogen fertilization, here the application of Cultan, were not successful in terms of yield stabilization during the first three years of the field trials. Successful implementation of such strategies in future will be a technical challenge that requires further research. Longer-term research is also required to observe a possible increase in weed and disease pressure over time if CSPs are not applied.

In the organic cropping systems, only the legumes (here pea and soybean) produced the same yields as in other cropping systems. Thus, the potential of legumes to supply nitrogen in cropping systems and thereby reduce the required nitrogen input should be adequately considered when planning future cropping systems. However, more agricultural production area will be required over time if legumes are to be included in the crop rotation of organic cropping systems to secure nitrogen supply. The same applies to the NOcsPS systems, if crops such as ryegrass have to be included into the rotation for reasons of weed management. This additional land requirement needs to be given adequate consideration when assessing the overall performance of cropping systems including environmental aspects and resource use. A promising strategy could be the valorization of the ryegrass or clover-grass mixture as feed and thus the integration of crop and animal production. A two-year intercropping with a clover-grass mixture also benefits weed control and can thus have multiple benefits.

With the detailed results obtained over the three years of the field trials, this study aims to provide initial insights into yields of various crops and cropping systems that could support transformative change in agriculture and also intends to stimulate further discussions. It is important to consider the limitations imposed by various effects, such as location factors, the influence of preceding crops and the transition of land to new management practices. However, it should be noted that the measures taken were consistent across the respective plots, allowing for the assessment of specific management practices such as wide crop rotations, soil management, and sowing patterns with respect to their impact on yield performance of cropping systems. Based on the recent findings, we assume, that NOcsPS cropping systems, that integrate best crop management practices including the careful use of mineral fertilizer can contribute to the establishment of future resilient cropping systems by combining crop production with the provision of other ecosystem services. To confirm this hypothesis, further research is necessary to evaluate the externalities related to different cropping systems and management practices and has to focus on the evaluation of ecosystem services beyond yield such as regulating services including biodiversity.

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Conflicts of interest

The authors declare that they do not have any conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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Supplementary information

Table. S1. Amounts of N Fertilization for UHOH

Crop		CI-1			CI-2			CII			NOcsPS I			NOcsPS II			NOcsPS III			NOcsPS IV		
		total N amount	Nmin	applied N ferti-lizer	total N amount	Nmin	applied N ferti-lizer	total N amount	Nmin	applied N ferti-lizer	total N amount	Nmin	applied N ferti-lizer	total N amount	Nmin	applied N ferti-lizer	total N amount	Nmin	applied N ferti-lizer	total N amount	Nmin	applied N ferti-lizer
Crop	Year	[kg ha^{-1}]	[kg]	[kg ha^{-1}]	[kg ha^{-1}]	[kg]	[kg ha^{-1}]	[kg ha^{-1}]	[kg]	[kg ha^{-1}]	[kg ha^{-1}]	[kg]	[kg ha^{-1}]	[kg ha^{-1}]	[kg]	[kg ha^{-1}]	[kg ha^{-1}]	[kg]	[kg ha^{-1}]	[kg ha^{-1}]	[kg]	[kg ha^{-1}]
	2020																					
WW1		241	41	200				233	33	200	199	39	160	205	45	160	200	40	160	210	50	160
WW2					250	50	200	242	42	200	198	38	160	201	41	160	194	34	160	202	42	160
WT								236	36	200	189	29	160	204	44	160	193	33	160	197	37	160
SB								199	61	138	166	56	110	173	63	110	168	58	110			
M		194	90	105	187	82	105	187	70	117	187	66	121	190	85	105	197	69	128	196	77	119
S																						
	2021																					
WW1		240	43	197				240	57	183	215	73	142	215	79	136	215	52	163	215	50	165
WW2*					240	58	172	240	57	173	215	64	141	215	62	143	215	59	147	215	58	147
WT								220	36	184	190	49	141	190	52	138	190	64	126	190	41	149
SB								160	41	119	140	33	107	140	38	102	140	30	110			
M		200	86	114	200	74	126	200	77	123	200	68	132	200	82	118	170	77	93	200	65	135
S																						
	2022																					
WW1		240	23	217				240	31	209	215	31	184	215	33	182	215	30	185	215	20	195
WW2*					240	25	205	240	63	167	215	30	175	215	39	166	215	38	167	215	34	171
WT								220	20	200	190	21	169	190	17	173	190	29	162	190	20	170
SB								160	35	125	140	31	109	140	31	109	140	26	114			
M		200	29	171	200	29	171	200	52	148	200	41	159	200	43	157	170	40	130	200	42	158
S																						

*WW2 – deduction for pre-crop soybean 10 kg N
Legend crops: WW1 – Winter wheat 1, WW2 – Winter wheat 2, WT – Winter triticale, SB – Spring barley, M – Maize, S – Soybean

Table S2. Amounts of N Fertilization for DaD

System		CII			NOcsPS I			NOcsPS II		
Crop	Year	total N amount [kg ha^{-1}]	Nmin [kg]	applied N fertilizer [kg ha^{-1}]	total N amount [kg ha^{-1}]	Nmin [kg]	applied N fertilizer [kg ha^{-1}]	total N amount [kg ha^{-1}]	Nmin [kg]	applied N fertilizer [kg ha^{-1}]
	2020									
WW1		140	a)	140	98	a)	98	98	a)	98
WW2		140	a)	140	98	a)	98	98	a)	98
WR		120	a)	120	84	a)	84	84	a)	84
SB		60	a)	60	42	a)	42	42	a)	42
M		140	a)	140	95	a)	95	95	a)	95
P		0		0	0		0	0		0
	2021									
WW1		140	a)	140	98	a)	98	98	a)	98
WW2*		140	a)	140	98	a)	98	98	a)	98
WR		120	a)	120	84	a)	84	84	a)	84
SB		80	a)	80	56	a)	56	56	a)	56
M		140	a)	140	98	a)	98	98	a)	98
P		0		0	0		0	0		0
	2022									
WW1		140	30	110	98	30	68	98	30	68
WW2*		140	30	110	98	30	68	98	30	68
WR		120	56	64	85	25	60	85	25	60
SB		90	30	60	63	30	33	63	30	33
M		142	10	132	109	10	99	95	10	85
P		0		0	0		0	0		0

*WW2 – deduction for pre-crop pea 10 kg N
a) values were not considered
Legend crops: WW1 – Winter wheat 1, WW2 – Winter wheat 2, WR – Winter rye, SB – Spring barley, M – Maize, P – Pea

Table S3. Amounts of applied CSPs for UHOH

Year	CSPPP	Herbicide			Fungicide			Insecticide			Growth rgulator		
	crop	Name	Active agent	Application rate [ha]	Name	Active agent	Application rate [ha]	Name	Active agent	Application rate [ha]	Name	Active agent	Application rate [ha]
2020	WW1	Atlantis WG	Iodosulfuron Mesosulfuron Iodosulfuron	500.0g	Tebucur	Tebuconazol	1.0l	Biscaya	Thiacloprid	0.3l	Cerone	Ethephon	0.4l
		Artus + Dash	Carfentrazone Metsulfuron	50.0 g + 1.0l									
	WW2	Atlantis WG	Iodosulfuron Mesosulfuron Iodosulfuron	500.0g	Tebucur	Tebuconazol	1.0l	Biscaya	Thiacloprid	0.3l	Cerone	Ethephon	0.4l
		Artus + Dash	Carfentrazone Metsulfuron	50.0 g + 1.0l									
	WT	Atlantis WG	Iodosulfuron Mesosulfuron Iodosulfuron	500.0g							Cerone	Ethephon	0.4l
		Artus + Dash	Carfentrazone Metsulfuron	50.0 g + 1.0l									
	SB	Axial	Pinoxaden	1.2l									
		Biathlon + Dash	Florasulam Tritosulfuron	70.0 g + 1.0l									
		Saracan	Florasulam	0.1l									
	M	MaisTer Power	Foramsulfuron Iodosulfuron Thiencarbazone	1.5l				Tricho-gramma evanescens	Tricho-gramma evanescens	1 card/plot ($135m^2$)			
		Lontrel	Clopyralid	167.0g									
	S	Stomp Aqua	Pendimethalin	1.5l									
		Spectrum	Dimethenamid-P	750.0ml									
2021	WW1	Herold	Diflufenican Flufenacet	0.6l	Aviator Xpro	Bixafen, Pro-thioconazol	1.0l	Karate Zeon	lamba-Cyhalotrin	75.0mL	Lotus CCC	Chlormequat	1.0l
		Ariane	Clopyralid Florasulam Fluroxypyr	1.5l	Elatus Era	Benzovindi-flupyr Pro-thioconazol	1.0l				Moddus	Trinexapac	0.2l
	WW2	Herold	Diflufenican Flufenacet	0.6l	Aviator Xpro	Bixafen, Pro-thioconazol	1.0l	Karate Zeon	lamba-Cyhalotrin	75.0mL	Lotus CCC	Chlormequat	1.0l
		Ariane	Clopyralid Florasulam Fluroxypyr	1.5l	Elatus Era	Benzovindi-flupyr Pro-thioconazol	1.0l				Moddus	Trinexapac	0.2l
	WT	Herold	Diflufenican Flufenacet	0.6l	Aviator Xpro	Bixafen, Pro-thioconazol	1.0l				Lotus CCC	Chlormequat	1.0l
											Moddus	Trinexapac	0.2l
	SB	Artus	Carfentrazone Metsulfuron	50g									
	M	MaisTer Power	Foramsulfuron Iodosulfuron	M									
	S	Artist	Flufenacet Metribuzin Clomazone	1.8kg									
		Centium	Pendimethalin	0.2l									

Table S3. Continued.

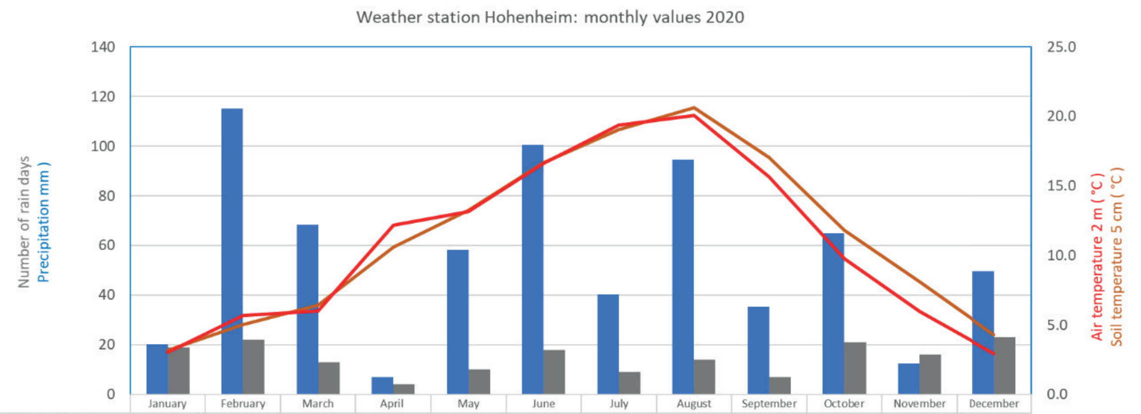
Year	CSPPP	Herbicide			Fungicide			Insecticide			Growth rgulator		
	crop	Name	Active agent	Application rate [ha]	Name	Active agent	Application rate [ha]	Name	Active agent	Application rate [ha]	Name	Active agent	Application rate [ha]
2022	WW1	Herold	Diflufenican Flufenacet	0.6l	Skyway Xpro	Bixafen Pro-thioconazol Tebuconazol	1.25l	Lambda WG	lamba-Cyhalotrin	150.0g	Moddus	Trinexapac	0.4l
		Artus	Carfentrazone Metsulfuron	50g									
		Ariane	Clopyralid Florasulam Fluroxypyr	1.5l	Skyway Xpro	Bixafen Pro-thioconazol Tebuconazol	1.25l						
	WW2	Herold	Diflufenican Flufenacet	0.6l	Skyway Xpro	Bixafen Pro-thioconazol Tebuconazol	1.25l	Lambda WG	lamba-Cyhalotrin	150.0g	Moddus	Trinexapac	0.4l
		Artus	Carfentrazone Metsulfuron	50g									
		Ariane	Clopyralid Florasulam Fluroxypyr	1.5l	Skyway Xpro	Bixafen Pro-thioconazol Tebuconazol	1.25l						
	WT	Herold	Diflufenican Flufenacet	0.6l	Skyway Xpro	Bixafen Pro-thioconazol Tebuconazol	1.25l				Moddus	Trinexapac	0.4l
		Artus	Carfentrazone Metsulfuron	50g									
		Ariane	Clopyralid Florasulam Fluroxypyr	1.5l									
	SB	Biathlon	Florasulam Tritosulfuron	70g									
		Artus + Dash	Carfentrazone Metsulfuron	50 g + 1.0l									
	M	Laudis	Tembotrione	1.7l				Tricho-gramma evanescens	Tricho-gramma evanescens	1 card/plot (135m²)			
		Mais Banvel	Dicamba	300g									
		Spectrum	Dimethenamid-P	1.2l									
	S	Artist	Flufenacet Metribuzin Clomazone	1.8kg									
		Centium	Pendimethalin	0.2l									

Table S4. Amounts of applied CSPs for DaD

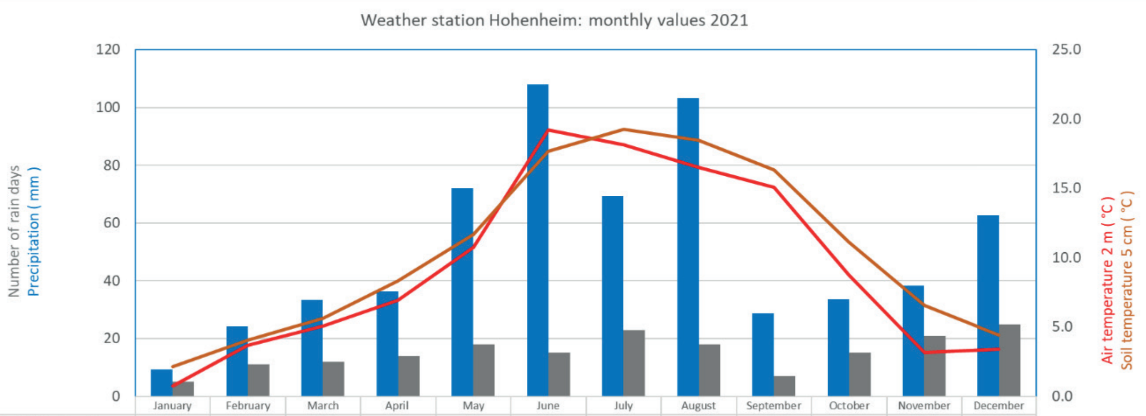
Year	CSPPP	Herbicide			Fungicide			Insecticide			Growth rgulator		
	crop	Name	Active agent	Application rate	Name	Active agent	Application rate	Name	Active agent	Application rate	Name	Active agent	Application rate
2020	WW1	Bacara FORTE	Flurtamone, Flufenacet, Diflufenican	1.0l									
	WW2	Bacara FORTE	Flurtamone, Flufenacet, Diflufenican	1.0l	Input Classic	Prothiocona-zol, Spirox-amine	1.25l						
	WR	Bacara FORTE	Flurtamone, Flufenacet, Diflufenican	1.0l	Pronto Plus	Tebuconazol, Spiroxamine	1.5l				Medax Top	Mepiquat-chlorid, Prohexadion-Ca	0.8l
	SB	Husar Plus	Mesosulfuron, Iodosulfuron, Mefenpyr	0.15l									
	M	Gardo Gold	Terbuthylazin, S-Metolachlor	3.0l				Trichogram-ma brassicae	Trichogram-ma brassicae	50 cards/ha			
		LAUDIS	Tembotrione	1.8l									
	P	Spectrum Plus	Dimethenamid-P, Pendimethalin	3.5l				Karate Zeon	lamba-Cyhalotrin	75.0mL			
								PIRIMAX	Pirimicarb	300g			
								Karate Zeon	lamba-Cyhalotrin	75.0mL			
								Shock DOWN	lamba-Cyhalotrin	0.15l			

Table S4. Continued.

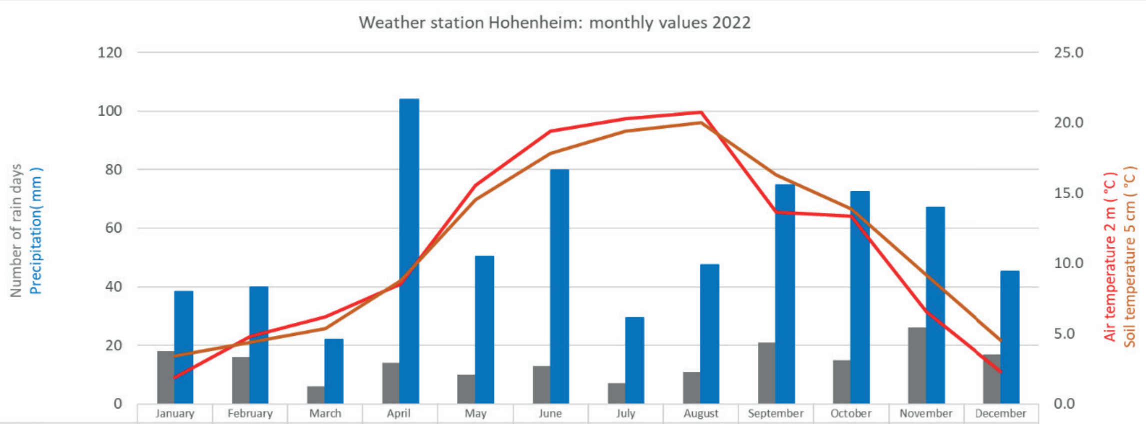
Year	CSPPP	Herbicide			Fungicide			Insecticide			Growth rgulator		
	crop	Name	Active agent	Application rate	Name	Active agent	Application rate	Name	Active agent	Application rate	Name	Active agent	Application rate
2021	WW1	Trinity	Pendimethalin, Chlortoluron, Diflufenican	1.5l									
	WW2	Trinity	Pendimethalin, Chlortoluron, Diflufenican	1.5l	Revytrex	Fluxapyrox-ad, Mefentri-fluconazol	1.2l						
					Comet	Pyra-clostrobin	0.4l						
	WR	Trinity	Pendimethalin, Chlortoluron, Diflufenican	1.5l	Elatus Era	Benzovindi-flupyr, Pro-thioconazol	0.8l				Medax Top	Mepiquat-chlorid, Prohexadion-Ca	1.0l
	SB	Husar Plus	Mesosulfuron, Iodosulfuron, Mefenpyr	0.15l									
	M	Gardo Gold	Terbuthylazin, S-Metolachlor	3.0l				Trichogram-ma brassicae	Trichogram-ma brassicae	50 cards/ha			
		LAUDIS	Tembotrione	1.8l									
	P	Boxer	Prosulfocarb	2.5l				Karate Zeon	lamba-Cyhalotrin	75.0mL			
		Stomp Aqua	Pendimethalin	2.2l				Karate Zeon	lamba-Cyhalotrin	75.0mL			
2022	WW1	Trinity	Pendimethalin, Chlortoluron, Diflufenican	2.0l									
	WW2	Trinity	Pendimethalin, Chlortoluron, Diflufenican	2.0l									
	WR	Trinity	Pendimethalin, Chlortoluron, Diflufenican	2.0l	Priaxor	Fluxapyroxad, Pyra-clostrobin	1.2l				Medax Top	Mepiquat-chlorid, Prohexadion-Ca	1.0l
	SB	Ariane C	Clopyralid, Fluroxypyr, Florasulam	1.0l									
	M	Gardo Gold	Terbuthylazin, S-Metolachlor	3.0l				Trichogram-ma brassicae	Trichogram-ma brassicae	50 cards/ha			
		LAUDIS	Tembotrione	1.8l									
	P	Boxer	Prosulfocarb	2.5l				Shock down	lamba-Cyhalotrin	150.0mL			
		Stomp Aqua	Pendimethalin	2.2l				Teppeki	Flonicamid	140,0g			
								Karate Zeon	lamba-Cyhalotrin	75.0mL			



	January	February	March	April	May	June	July	August	September	October	November	December
Precipitation (mm)	20.2	115.2	68.40	7.00	58.1	100.5	40.3	94.7	35.3	65	12.4	49.6
Rain days	19	22	13	4	10	18	9	14	7	21	16	23
Soil temperature 5 cm (°C)	3.2	5.0	6.4	10.6	13.3	16.7	19.1	20.6	17.0	11.8	8.1	4.3
Air temperature 2 m (°C)	3.0	5.7	6.0	12.2	13.2	16.6	19.4	20.1	15.6	9.8	6.0	2.9



	January	February	March	April	May	June	July	August	September	October	November	December
Precipitation (mm)	9.4	24.3	33.3	36.2	72	107.9	69.3	103.3	28.7	33.6	38.4	62.7
Rain days	5	11	12	14	18	15	23	18	7	15	21	25
Air temperature 2 m (°C)	0.8	3.7	5.1	7.0	10.8	19.2	18.1	16.5	15.1	8.8	3.2	3.4
Soil temperature 5 cm (°C)	2.2	4.1	5.7	8.3	11.7	17.7	19.3	18.5	16.3	11.1	6.5	4.4



	January	February	March	April	May	June	July	August	September	October	November	December
Rain days	18	16	6	14	10	13	7	11	21	15	26	17
Precipitation (mm)	38.3	40	22.1	104	50.3	79.8	29.5	47.5	74.8	72.6	67.2	45.3
Air temperature 2 m (°C)	1.9	4.8	6.2	8.5	15.5	19.4	20.3	20.7	13.7	13.4	6.6	2.3
Soil temperature 5 cm (°C)	3.4	4.4	5.4	8.8	14.5	17.8	19.4	20.0	16.3	13.9	9.2	4.5

Fig. S1. Weather Charts of UHOH for the years 2020–2022

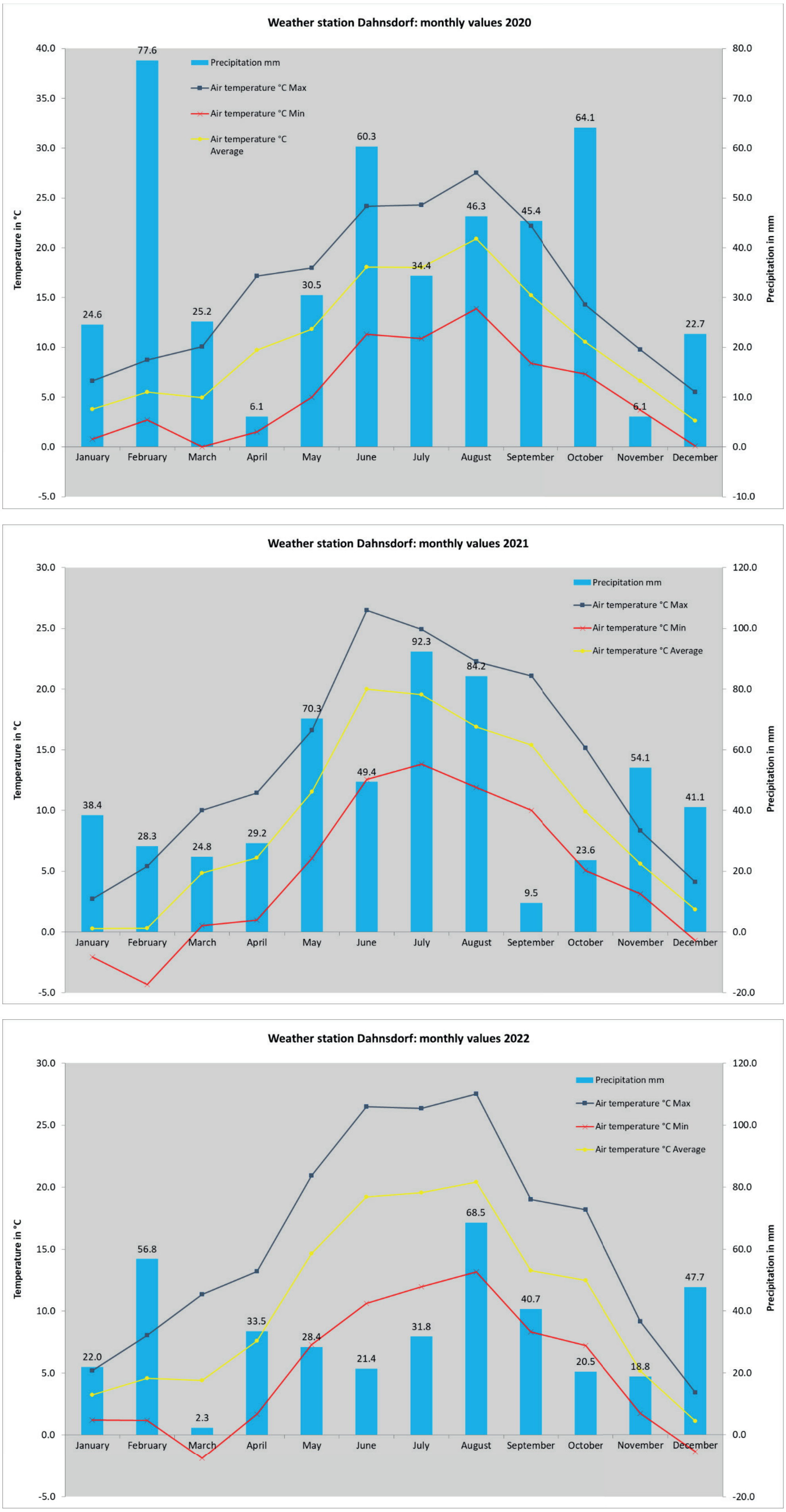


Fig. S2. Weather Charts of DaD for the years 2020–2022