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Comparison of resilience of different plant teams to drought and temperature extremes in Denmark in sole and intercropping systems

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ABSTRACT

Intercropping (IC) can reduce nitrogen fertilizer requirements, supress weeds, and improve crop yields and yield stability. Three field trials were conducted in Denmark in 2018 with intercropping and sole crops (SC) using spring wheat, barley, faba bean and field pea to compare productivity under five fertilizer levels.

The trials were carried out using in a split-plot design with four. Anomalous weather during the 2018 cropping season created drought conditions and high temperatures above 31°C.

No effect of fertilizer treatment was found, and total dry matter and grain yields were supressed in all systems. Wheat grain yields averaged 2.14 t ha^{-1} across systems, ranging from 1.58 t ha^{-1} as a component of the IC to 2.44 t ha^{-1} as SC, and barley grain yields averaged 2.35 t ha^{-1}. Faba bean yielded 1.78 t ha^{-1} as SC, but failed in the IC. Pea failed in both systems. Intercropping barley with cover crops had no effect on grain yield or total dry matter. These results suggest that intercropping provided no production advantage during a drought and illuminate the need to continue conducting research and breeding on drought-resistant cultivars.

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Intercropping; cereal-legume; drought; barley; cover crop; field trial; land equivalent ratio

Introduction

Crop productivity is projected to increase in northern Europe under multiple climate change scenarios due to increasing precipitation and warmer temperatures, and to decrease in southern Europe due to increasing aridity (Iglesias et al. 2012; Stagge et al. 2017). The already perceptible northward shift in European agro-ecological zones is predicted to accelerate in the coming decades (Ceglar et al. 2019), including a detectable northward shift of drought (Stagge et al. 2017). While farmers in northern Europe could stand to gain from overall climate change in the coming decades from the increasing temperature and CO_2 concentration, gains may be countered by the predicted increase in frequency, duration and spatial extent of extreme weather events (Iglesias et al. 2012; Grillakis 2019). The increasing rainfall predicted for northern Europe can adversely affect field accessibility, lodging and flooding in fields (Trnka et al. 2015). These natural hazards leave farming systems vulnerable to economic stress and present challenges to ensuring food security (Ray et al. 2015).

The 2003 summer heat wave in Europe followed by a prolonged drought period caused widespread crop damage, and the 2018 record-breaking high temperatures and drought in northern and central Europe caused severe crop failures (Beillouin et al. 2020). While wetter conditions in southern Europe made up for some of the grain losses in other regions in 2018, Europe suffered an overall loss of grain harvest by 4.8% compared to harvests in 2017 (EUROSTAT 2020).

Extreme temperatures and water stress are known to affect wheat productivity (Hossain et al. 2012; Trnka et al. 2015; Vignjevic et al. 2015; Mäkinen et al. 2018), and winter wheat yield in Europe was especially low in 2018 (Beillouin et al. 2020). High temperature reduces yield by accelerating plant development, but the most sensitive phase to high temperature stress are anthesis and grain-filling stages (Porter and Gawith 1999; Vignjevic et al. 2015; Mäkinen et al. 2018). Temperature between 27° C and 31° C and higher around anthesis can adversely affect pollen fertility, resulting in fewer grains, and reduces grain filling to produce lighter grains (Trnka et al. 2014).

High temperature coupled with low precipitation result in a negative feedback where high temperature drives more evapotranspiration in an already stressed

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plant, which results in greater water deficit in the plants (Vignjevic et al. 2015). The water deficit also reduces the cooling of crops, affecting their overall development.

Drought and high temperature also adversely affect legumes, perhaps more than cereals. Though varietal phenotype matters (Gollner et al. 2019), the broad leaves and canopy of legume plants, compared to wheat, result in higher rates of evapotranspiration (Müller et al. 1986), and their shallow rooting systems limit the root soil profile resulting in more rapid exhaustion of the soil water than cereals (Müller et al. 1986). Faba beans are particularly sensitive to both high temperature and drought stress, especially during the reproductive phase (Müller et al. 1986; Lavania et al. 2014). Water stress is known to reduce N_2 fixation in legumes, even more than both carbon and nitrate assimilation, through decreasing nodule mass and number (Serraj et al. 1999), although Sepúlveda-Caamaño et al. (2018) found that some Rhizobia strains are drought tolerant. Krogman et al. (1980) suggest that water stress also limits yield in legumes, since soil moisture and N_2 fixation are highly correlated.

Farming systems are presently impacted by global climate change, requiring adaptive measures. Alternative agricultural systems and practices are increasingly necessary to achieve yield stability and system resilience (Malézieux et al. 2009). Intercropping (IC) – the combination of two or more crops with temporal and spatial overlap – is one such system of agricultural intensification that can improve yields, reduce water use, and reduce greenhouse gas emissions (Jensen et al. 2020) and NO_3. The increased canopy of an intercropped field can reduce soil moisture evaporation and improves both water use efficiency and nutrient use efficiency through resource partitioning between morphologically different crops, and vegetation mixtures can specifically help with yield stability in drought conditions (Van den Hoof and Lambert 2016). Cereal-legume IC systems have the added benefit of nutrient use efficiency, with the functional capture of atmospheric N_2 by the legume (Karpenstein-Machan and Stuelpnagel 2000; Andersen et al. 2005; Chapagain and Riseman 2014; Jensen et al. 2020; Rodriguez et al. 2020). For this reason, IC is considered an effective practice in organic cropping systems. Experimental trials have shown that different levels of mineral N fertilizer inputs do affect yield (Hauggaard-Nielsen and Jensen 2001; Sobkowicz and Śniady 2004; Ghaley et al. 2005), but great variability is found between crop combinations and field conditions. Less is known about the performance of IC systems in drought conditions.

The objectives of these field trials were to test the hypotheses that productivity gains can be achieved in intercropping systems compared to sole cropping, and that productivity would be affected by different fertilizer amounts and sources. The severe drought that occurred in northern Europe in 2018, coupled with record high temperatures, provides an opportunity to also report on the performance of these crops and cropping systems under extreme weather conditions. Thus, a final objective of this paper is to report on the performance of a wheat-legume intercrop and a barley-clover/rye fodder mixture relative to sole crops under drought conditions, and the differential effect of drought on the targeted crop species.

Materials and methods

Study site

The study was carried out in northern Europe at the field research station at Højbakkegård, in Taastrup, Denmark (55°40′N, 12°18′E), which is managed by the Department of Plant and Environmental Sciences, University of Copenhagen. The fields are located at 25-27 m a.m.s.l. The trial was carried out in 2018 between May and August under rainfed conditions.

Northern, central and eastern Europe experienced extreme temperatures and dry conditions from March to August in 2018 (Beillouin et al. 2020). The average daily temperature during the trial period from May 1 through August 8 as recorded at the meteorological station at the site was 18.9°C, which was significantly higher than the average of 15.7° C for the previous five years ($p < 0.001$) (Table 1). The maximum temperature in the 2018 season was 32.6° C on day 79 after sowing, with two consecutive days over 31.0° C (Figure 1). Precipitation during the period was 48 mm, which is 23% of the five-year average of 209 mm ($p < 0.001$).

Field environments

Three field trials were conducted in two different field environments. Trial 1 (T1) was on an open field with a history of conventional management and cultivated with annual grain crops at least since 2000, with the application of fertilizer, herbicide and pesticide inputs. Trials 2 (T2) and 3 (T3) were carried out on fields 100 m wide situated between short-rotation woody crop shelterbelts established in 1995 as a combined food and energy system (CFE) (Ghaley and Porter 2013). Since 2000, the CFE system had been in crop rotations of barley under-sown with clover/rye, clover/rye, and wheat. Prior to the current trial, the CFE system was managed organically, without the use of fertilizers, herbicides or pesticides. Nutrient sources were

Table 1. Mean daily air temperature and standard deviations, and sum of total precipitation at the trial site in the dates of the investigation, compared to the five-year average for the same time. All pairs between time periods are significantly different at *p*<0.001 (one-sample, one-way t-tests).

	Average daily temperature (°C)				Monthly precipitation (mm)		
Month	*2018*	*±s.d.*	*5 yr average*	*±s.d.*	*2018*	*5 yr average*	*±s.d.*
May	15.5	3.4	11.9	3.2	22.8	51.5	21.9
June	17.6	1.9	15.7	2.4	5.1	63.1	16.7
July	20.5	2.6	17.4	2.6	18.1	67.4	32.4
August	21.9	1.7	17.8	1.9	2.0	27.1	11.3
	means 18.9		15.7		sums 48.0	209.0	

mainly derived from biological nitrogen fixation and the application of animal manure. Because of the history of organic management, the T2 and T3 fields had an especially high incidence of thistle. Therefore, where perennial weeds were present in the fields, manual weeding took place periodically in the first five weeks of the trial.

The soil in the three fields were sandy loam Luvisol (FAO-UNESCO 1997). The soil bulk density of T1 field was 1.31 g cm^{-3} (s.d. = 0.13, n = 4) and lower than in the T2 field (mean = 1.50 g cm^{-3}, s.d. = 0.09, n = 4). This difference was significant (t-test 0.05, $p = 0.048$). The soil water content for both fields was 13.6% by weight at the time of collection.

Experimental design

Three field trials, each consisting of three cropping systems (Table 2), were conducted under a split-plot design with four replicates, with crop systems as main plots in four replicates and fertilizer treatments as subplots. Crop rows were 100 m long and 6 m wide, sown with a 1 m pathway between the rows. Each row consisted of a single cropping system. Seeding densities followed common practices by commercial farmers.

The crop combinations employed are in Table 2. Crop used in T1 and T2 were faba bean (*Vicia faba* L., cultivar unknown), spring wheat (*Triticum aestivum* L., cultivar unknown), and field pea (*Pisum sativum* L., cultivar Javlo).

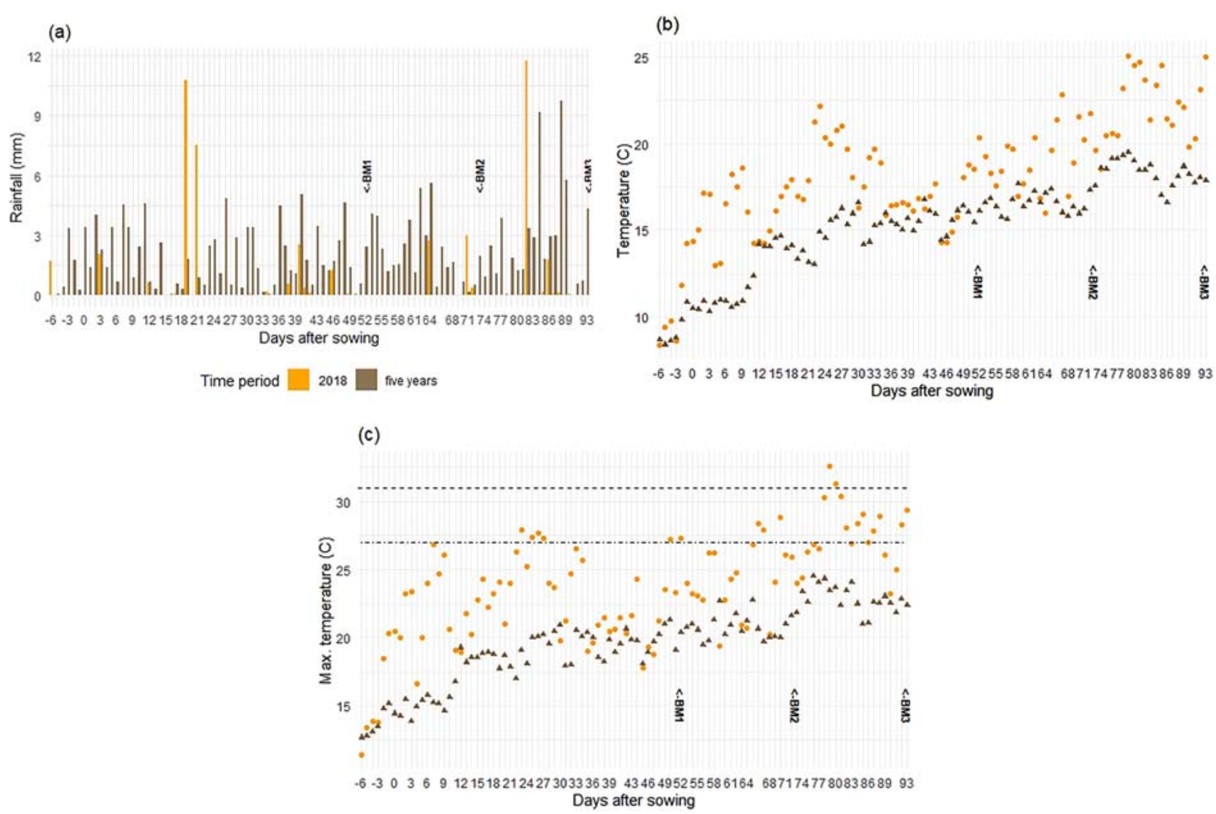

Figure 1. Weather during the study season (May 1 – August 8) for 2018 (light) and a five-year average (2014-17, 2019; dark), with (a) daily precipitation (mm), (b) average daily temperature (°C), and (c) daily maximum temperature (°C). Biomass sampling dates are indicated by BM. Critical maximum temperatures are indicated in (c) at 31°C (dashed line) and 27°C (dash-dot line) (Trnka et al. 2014).

Table 2. Characteristics of the 2018 field trials.

Descriptor	Trial 1 (T1)	Trial 2 (T2)	Trial 3 (T3)
Field environment	open field	shelterbelt	shelterbelt
Field management history	conventional	organic	organic
Fertilizer treatment (see Table)	A	A	B
Cropping systems	wheat SC faba bean SC wheat-faba bean IC	wheat SC field pea SC wheat-pea IC	barley SC barley-clover/rye IC barley-clover/rye-chicory IC
IC design	additive (75% of SC)	additive (75% of SC)	Additive (100% of SC)
Sowing (in order of crops above)	Seed density (m^2) 80 400 60:300	Seed density (m^2) 50 400 38:300	Seed rate (kg ha^{-1}) 190 190:30 190:30:10

Table 3. Fertilizer application for (a) trials 1 and 2 with wheat-grain legume intercropping, and (b) trial 3 with barley-living mulch intercropping.

Treatment no.	Total N fertilizer (kg N ha^{-1})	Total chemical fertilizer (22-3-8) (kg ha^{-1})	Total organic fertilizer (9-3-4 + 2S) (kg ha^{-1})
(a) Trials 1 & 2			
F1	0	-	-
F2	125	285	694
F3	125	570	-
F4	180	420	1000
F5	180	800	-
(b) Trial 3			
FT1	50	238	-
FT2	100	476	-
FT3	150	714	-
FT4	200	952	-
FT5	250	1190	-

Crop varieties were chosen for their synchronicity in maturation, within one week of each other to facilitate combined harvesting, reducing labour and machinery expenses. Spring barley (*Hordeum vulgare* L., cultivar unknown) was at the center of T3, coupled with a fodder mix [DLF ForageMax 47, containing 35% white and red clovers (*Trifolium repens* L. and *T. pratense* L., respectively) and rye (65%)], and chicory (*Cichorium intybus* L., cv Spadona). The chicory was added to the cover crop for its role in improving soil structure with its taproot. The intercrops in T1 and T2 were established using an additive design with 75% plant density of both sole crops.

The five fertilizer treatments in T1 and T2 consisted of applications of a mix of organic and chemical fertilizers in different amounts and proportions within rows (Table 3 (a)). The fertilizer rates were designed to reflect the local nitrogen fertilizer application rates in Denmark, where spring wheat is allowed to be fertilized between 165-181 kg N ha^{-1} depending on the soil types and the cropping history of the fields (Landbrugsstyrelsen 2020). Where organic and chemical fertilizer were combined (F2 and F4), each type constituted 50% of the nitrogen rate. The use of organic and chemical fertilizer provides a more complete profile of nutrients due to the slow release of nutrients from the organic source, which can have improved growth and yield effects on crops. The use of chemical and organic fertilizer also provides insights into how much of the chemical fertilizer can be substituted with organic fertilizer, to reduce the fossil fuel-based chemical fertilizer for crop production. In the third trial, where spring barley is used, only chemical fertilizer was applied, and in five different amounts, to look for a threshold point at which it is economically beneficial to apply the fertilizer and to assess the incremental change in yield with increase in fertilizer application until the fertilizer effect flattens out with further addition of chemical fertilizer. The national fertilizer guidelines for spring barley were 141-159 kg N ha^{-1} (Landbrugsstyrelsen 2020), and we have pushed fertilizer rates by 1.6 times higher to assess the limit of the fertilizer effect. (Table 3 (b)). The fields were sown and fertilized in the beginning of May 2018.

Data collection

The field trials were established on 7 May 2018. Aboveground biomass was sampled three times during the growing season, at 52 (BM1), 74 (BM2), and 93 (BM3) days after sowing (DAS). The final harvest corresponded to the physiological maturity of both crops, including the full development of the grains. Plant material was collected from each plot in an area of 0.25 m^2 for BM1 and BM2, and in 0.50 m^2 for BM3 and grains. All samples were oven dried at 65° C for 48 h. Oven-dry weights are reported here.

In T1 and T2 (wheat-bean, wheat-pea), the biomass from each crop was separated and subsequently weighed. For T3 (barley-cover crop) all the biomass in the sample was weighed together; and only at the final harvest was barley grain separated and weighed. Total dry matter (TDM) values reported for BM3 include both straw and grain. Grain yield (GY) values reported here are based on a subsample of grains separated from the collected biomass.

Statistical analysis

Response variables of interest in this study were aboveground biomass, assessed as total dry matter (TDM), and grain yield (GY). Independent variables considered were fertilizer treatment and replicate. Linear mixed models were used to assess the effect of fertilizer application on TDM and GY among the cropping systems at each sample date. The first model used a combination of crop system and treatment as fixed effects and block as a random effect. Where there was no fertilizer treatment effect, the model consisted of TDM or GY as dependent variables and analyzed separately for each collection date using a one-way ANOVA with the crop system as fixed effect and block:treatment as random effect. To report significance from the model procedures, the mean model standard error and *p* values from Tukey pairwise contrast analyses are reported. All analyses were carried out in R Studio v1.3.1093 (R Core Team 2020) with the lme4 (Hothorn et al. 2008) and multcomp (Bates et al. 2015) packages. Differences for all analyses are considered significant if $p < 0.05$. Missing values in the data and extreme outliers from human error were replaced with the average of the other three replicates.

Results

Fertilizer treatment effects

Overall, there was no effect of fertilizer rate on total dry matter (TDM) or grain yield (GY) in any cropping system in any trial (Figure 2). Given the lack of fertilizer treatment effect, for subsequent analyses, aggregate datasets across fertilizer treatments and blocks (n = 20) were used to evaluate system and crop productivity.

Wheat-faba bean and wheat-pea intercrop

Total dry matter

The legume crops performed poorly throughout crop development, yielding consistently well below wheat SC and the IC (Table 4(a)). At crop maturity, in T1, with wheat-bean, the TDM for the wheat SC was similar to the IC, and both systems produced more than the pea SC. In T2, with wheat-pea, the three systems were different, with wheat SC > IC > pea SC (all $p < 0.0001$). Biomass decreased between 74 and 93 DAS in all three systems in T1, indicating senescence, but not in T2, where the wheat SC gained total dry matter.

The legume crops in the two IC systems largely failed (Table 4(b)), with 0.05 t ha^{-1} of TDM at final harvest for the faba bean component in T1, and 0.14 t ha^{-1} for peas in T2.

Grain

Grain yield (GY) was highly correlated to TDM at final harvest (CORR r = 0.97). With all crop data pooled, the average grain yield in T1 (2.10 t ha^{-1}) was greater than in T2 (1.59 t ha^{-1}) ($p < 0.001$). In T1, the bean SC GY (1.78 t ha^{-1}) was less than the wheat SC (2.32 t ha^{-1}) ($p = 0.003$). The GY of the IC and legume SC were lower in T2 than in T1 (Table 4(a)).

In T2, the GY were significantly different among the three cropping systems, with wheat SC > IC > pea SC

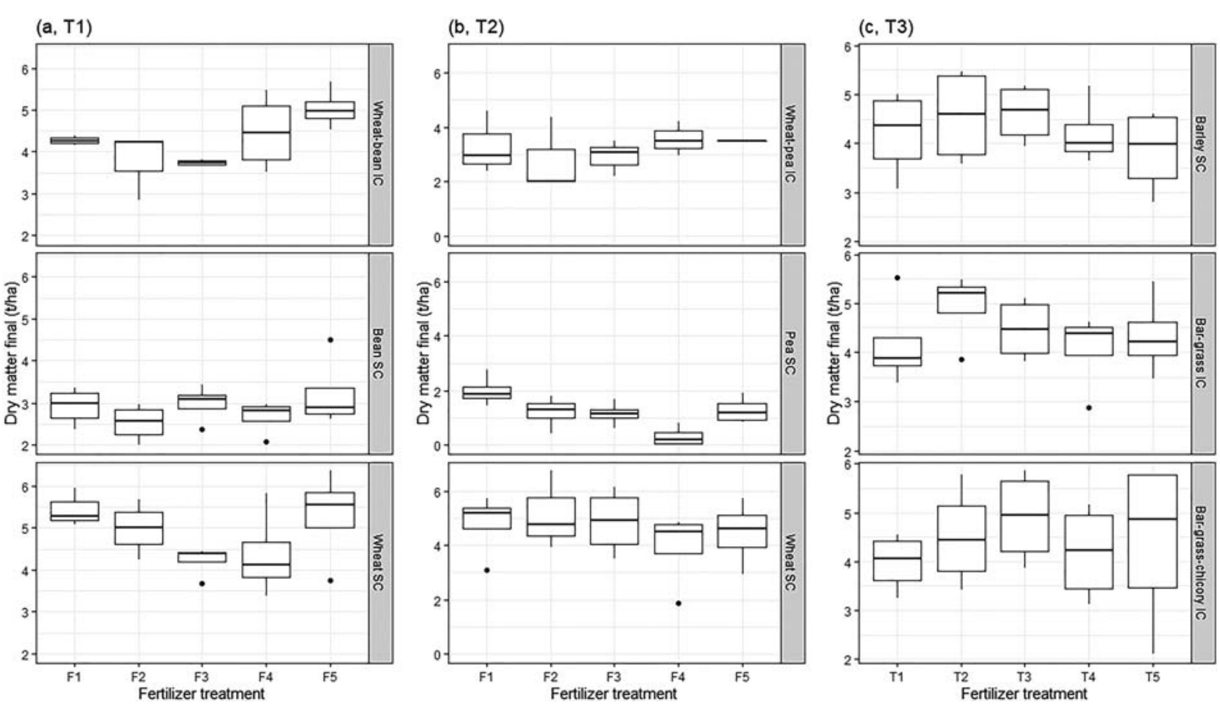

Figure 2. Fertilizer treatment, from low to high (see Table 2), effect on dry matter at crop maturity for each cropping system in (a) T1, wheat-bean IC; (b) T2, wheat-pea IC; and (c) T3, barley-cover crop IC. Boxes on raw data (n=4). No significant effects were found in any of the cropping systems.

(Table 4(a)). The GY of bean SC (1.78 t ha^{-1}) was 2.9 times that of the pea SC (0.62 t ha^{-1}) ($p < 0.001$). Grain yield of the legume plants in the IC systems were negligible, at 0.01 t ha^{-1} of bean in T1, and 0.07 t ha^{-1} GY of pea in T2, and not significantly different (Table 4(b)).

Land equivalent ratio (LER)

In T1, the LER was 1.0 at the earliest growth stage and less than 1.0 at later stages of crop development and for GY (Table 5), indicating that there was no advantage to the intercropping compared to sole cropping, and even a slight disadvantage. In T2, the LER was higher in the earlier stages of crop development than at crop maturity, where even the wheat IC declined. The very low LER in T2 was due to an increase in total dry matter in the SC between 74 and 93 DAS and no increase in the wheat IC.

Barley-based systems

There were no significant differences in TDM or GY at crop maturity among the barley-based cropping systems (T3) (Table 6). The only difference was at 74 DAS, where the barley SC had a higher TDM than the barley-clover/rye system ($p = 0.002$). TDM for these barley-based systems was also similar to the TDM for the wheat SC in T1 and T2 and the wheat-bean IC in T1. The GY for barley in all three of these systems was also similar to GY for wheat in T1 and T2.

Discussion and conclusions

The impact of drought on the fertilizer effect

The first objective of this study was to determine whether different rates and sources of fertilizer N affected crop productivity. The rationale for sowing crops together in mixed rows is that legumes grow more slowly in the early stages than cereals. Under normal growing conditions, this difference is advantageous for the cereal to exploit the available nitrogen, leaving little for legumes, which forces them to fix nitrogen to meet its own requirements. In these field trials, as shown in Figure 2, there were no significant differences in crop productivity that could be attributed to fertilizer rate or source in any of the three trials. The likely explanation is that the limiting resource in the system was water, rather than nutrients. This is contrary to findings, where increasing N fertilization countered the decrease in crop DM production with increasing drought stress (Tarighaleslami et al. 2012; Sedri et al. 2019). We included the application of organic N fertilizers in trials 1 and 2 because it can help optimize N uptake by plants and N loss from the system due to the slow release with mineralization, as opposed to the bulk availability of mineral N fertilizers. The lack of rain, however, likely supressed N mineralization of the organic fertilizer in T1 and T2, therefore inhibiting the expected slow release and availability of nutrients during the season. The lack of water may also have inhibited nodule formation in the legumes, thereby suppressing N_2 fixation processes normally present (Plies-Balzer et al. 1995; Serraj et al. 1999; Marino et al. 2007; Prudent et al. 2016).

Extreme weather effects on crop productivity

A second objective of the study was to evaluate the relative productivity of intercropping compared to sole crops. The occurrence of the extreme weather during the trial period confounds the results but presents an opportunity to amend the hypothesis to look into the effects of drought and temperature stress on the

Table 4. Yields in tons ha^{-1} of total dry matter (TDM) at three sample times and grain yield (GY) in trial 1 (T1) and trial 2 (T2) (a) among cropping systems and (b) between the IC component crops. Values are means across blocks (n=4) and treatments (n=5) (n=20). In (a) and (b) separately, superscript letters indicate significant differences among (a) crop systems and in (b) between IC crops across trials.

		Total dry matter (t ha^{-1})						GY (t ha^{-1})	
Crop system		52 DAS	±se	74 DAS	±se	93 DAS	±se	93 DAS	±se
(a)	Crop system								
T1	bean SC	1.57 ^{c}	0.24	3.58 ^{b}	0.43	2.86 ^{b}	0.22	1.78 ^{ab}	0.14
	wheat SC	3.63 ^{a}	0.33	5.55 ^{a}	0.46	4.84 ^{a}	0.34	2.32 ^{a}	0.16
	IC	3.66 ^{a}	0.27	5.21 ^{ab}	0.36	4.36 ^{a}	0.34	2.08 ^{a}	0.19
T2	pea SC	1.42 ^{c}	0.40	2.00 ^{d}	0.54	1.19 ^{c}	0.29	0.62 ^{c}	0.18
	wheat SC	2.61 ^{b}	0.34	3.32 ^{b}	0.47	4.62 ^{a}	0.48	2.44 ^{a}	0.27
	IC	2.33 ^{b}	0.33	3.49 ^{b}	0.52	3.17 ^{b}	0.37	1.60 ^{b}	0.20
	model s.e.	0.273		0.386		0.275		0.152	
(b)	IC component								
T1	bean IC	0.12^{c}	0.02	0.09 ^{c}	0.02	0.05 ^{c}	0.01	0.01 ^{c}	0.01
	wheat IC	3.32^{a}	0.14	5.13 ^{a}	0.20	4.54 ^{a}	0.20	2.21 ^{a}	0.11
T2	pea IC	0.25 ^{c}	0.05	0.23 ^{c}	0.05	0.14 ^{c}	0.02	0.07 ^{c}	0.01
	wheat IC	2.11^{b}	0.15	3.26 ^{b}	0.28	3.09 ^{b}	0.21	1.58 ^{b}	0.11
	model s.e.	0.145		0.249		0.203		0.106	

Table 5. Land equivalent ratios (LER) for trials 1 and 2, the wheat-legume intercrop systems. Values are means across blocks and treatments (n=20).

	Trial 1, wheat-bean				Trial 2, wheat-pea			
LER	BM1	BM2	BM3	GY	BM1	BM2	BM3	GY
LERp legume	0.078	0.030	0.017	0.008	0.184	0.118	0.108	0.096
LERp wheat	0.918	0.934	0.947	0.964	0.825	0.991	0.673	0.646
LER	1.00	0.96	0.96	0.97	1.01	1.11	0.78	0.74

intercropping systems and component crops. The results from these trials demonstrate that drought negates any potential advantage in productivity of intercropping over sole cropping. Under normal experimental conditions, intercropping of cereal-legume systems often yields LER values above 1.0, indicating a production advantage (Hauggaard-Nielsen et al. 2008), which was not the case in the present trials (Table 5). The near-total failure of the faba bean and pea components of T1 and T2 explains the low LER values. The barley-rye-chicory intercropping systems performed no better than barley SC, with whole-system total aboveground biomass and barley grain yield being the same in all three cropping systems (Table 6). Since there is no evidence that the presence of the companion cover crops helped or hindered barley production during this drought season, it could be beneficial for farmers to include cover crops with barley for their ecosystem services, such as weed suppression, soil stabilization, soil water management, and pollinator services (Kaye and Quemada 2017).

The drought caused near collapse of the legumes in the intercropping systems and, coupled with weed competition, almost total collapse of the pea SC system (Table 4). Legumes are known to recover from drought if there is some relief prior to the reproductive stage (Prudent et al. 2016), but at this field site in 2018 there was virtually no effective precipitation during the entire cropping period.

The 2018 drought apparently decreased cereal and legume grain production compared to normal years in the Danish national agricultural trials (Table 7). In 2018, the national trial GY for all the study crops was lower than a four-year average, andthe production in our trials was considerably lower even than the 2018 average.

Impacts of extreme weather on sole and intercrops

Given the lack of effect in the fertilizer treatment, we must turn to the water stress and temperature to explain these results. There was virtually no effective precipitation during the trial cropping season, thus requiring the plants to utilize the residual soil moisture, which only diminished over time. Water stress in the early growth period can reduce biomass, which correlates with reduced grain production (De Costa et al. 1997). The simultaneous emergence of weeds in the CFE fields (T2, T3) may have caused early N competition and lower biomass. The rate of leaf senescence increases under water stress (Senapati et al. 2019), and early senescence can be a drought escape response. This physiological response may explain the loss of biomass in all three crop systems in T1between 74 and 93 DAS, although this did not happen in T2 or T3. Despite the biomass loss in T1, both TDM and GY at final harvest were greater than in T2, confounding any mechanistic explanation of these results.

The deep root systems in cereal crops and the relatively short roots in legumes may explain their relative performance in these trials (Gonzalez-Rizzo et al. 2009; Abdelhamid 2010). Under normal water conditions, wheat and barley have robust root systems that reach laterally 12–18 in. and to depths of 3–6 feet, which afford access to more water resources (Weaver 1926). Roots of legumes are generally shorter than cereals, and under drought their root systems are smaller (Gonzalez-Rizzo et al. 2009; Abdelhamid 2010). This disparity in root system size may have resulted in the cereals having an advantage over legumes in exploiting the existing soil water.

Pea was most adversely affected by the drought in both the IC and SC systems. Though pea has been cultivated in Denmark for a long time, it is not regarded as a good crop in the wet northern Europe, for its dense canopy structure reduces air circulation and drying (Thompson and Taylor 1982). Faba bean is regarded as one of few grain legume crops suitable to the northern Europe climate (Thompson and Taylor 1982), while it is also known for its high sensitivity to water stress (Müller et al. 1986). Some attempts were made in the 1980s to increase the cultivation of faba beans in northern Europe to offset the high costs of importing soy for animal feed, but its yield variability compared to cereals makes it unattractive to producers (Thompson and Taylor 1982). The relative success of faba bean sole cropped in this trial indicates that it is at least better adapted to drought than pea, perhaps because of its ability to compete with weeds.

Cultivars perform differently under different conditions: in wheat, Mäkinen et al. (2018) showed in a literature review that 78 percent of 525 cultivars

Table 6. Average TDM (t ha^{-1}) at three times and GY (t ha^{-1}) for the three crop systems in Trial 2 (barley). Values are means of 20 plots, across treatments and blocks. Cropping systems with different letters are significantly different ($p < 0.05$), and no letters means there are no differences.

	Total dry matter (t ha^{-1})						GY (t ha^{-1})	
Crop system	52 DAS	±se	74 DAS	±se	93 DAS	±se	93 DAS	±se
Barley SC	3.63	0.23	4.28 [a]	0.28	4.31	0.17	2.29	0.09
Barley + clover/rye	3.44	0.23	3.24 [c]	0.25	4.40	0.18	2.31	0.10
Barley + clover/rye + chicory	3.52	0.23	3.93 [ab]	0.24	4.40	0.24	2.45	0.14
s.e. model	0.299		0.305		0.215		0.197	

reported on in Europe were found to suffer losses under drought conditions. Crop breeding has traditionally been the focus in agricultural adaptation to a changing world, and perhaps now more than ever breeding must be conducted for traits that increase resilience in the face of a changing and variable climate. Given the differences among cultivars, selection is an important mitigation response to increasing climate variability and extremes (Trnka et al. 2015). Senescence as a drought escape response is one of the main limitations to production, and thus, breeding crops to delay senescence under water stress – or, stay-green breeding – is an important avenue to maintaining yield stability (Vignjevic et al. 2015; Senapati et al. 2019).

Both rising local temperatures and extreme temperatures associated with global climate change have been predicted to have deleterious effects on crop yields (Wheeler et al. 2000). Shifting production areas northward is a proposed solution for the drying and warming of southern Europe, but modeling suggests that the increase in climate variability, especially the increasing frequency of extreme weather events that result in yield losses, outweigh the gains from shifting (Trnka et al. 2015; Ceglar et al. 2019).

In a study on the perceptions of climate change (Woods et al. 2017), Danish farmers were found to have little concern about climate change impacts on their farms, but that those who have more concern are likely to have an adaptive response to negative impacts. In the face of uncertain impacts of future climate change, they prefer to take incremental and flexible adaptations rather than switching to different cropping systems such as using intercrops or increasing rotations. Though Danish agriculture is mostly rainfed, some irrigation during drought could improve performance in the intercropping system. Studies should be conducted in northern Europe to determine the optimal times during crop development for irrigation (Zhang et al. 2008).

Table 7. Grain yield (t ha^{-1}) in sole cropping of the crops used in this study from the Danish national trials (average of all cultivars within each year) over four years and in 2018, these study trials, and percent of GY in the present trials to the 2018 national trials. (Source: SortInfo.dk)

	Grain yield (t ha^{-1})			
Crop	*National trials, 4-y average*	*National trial, 2018*	*Present study*	*% present study to 2018 national trials*
Spring wheat	6.43	5.84	2.40	41
Spring barley	7.34	6.46	2.29	37
Faba bean	6.56	3.10	1.78	57
Field pea	4.93	4.30	0.62	14

In this paper, we report on the performance of wheat-legume intercropping systems and a barley-clover/rye-chicory mixture relative to sole crops under drought conditions. There were no effects of the wide range of fertilizer treatments on any of the cropping systems, likely negated by the drought conditions. While the productivity of all crops in all cropping systems was below levels from average weather years, the wheat performed relatively well compared to the legumes in both sole cropping and intercropping systems. Barley performed equally well as a sole crop and intercropped with forage. No advantage was found in any of the intercropping systems over sole crops, and legumes failed almost entirely in the intercrop. In these trials, widely cultivated varieties were used, but in the face of climate change, farmers will want to sow cultivars that are resilient to climate extremes. The differential performance of these crops under drought is a reminder of the need to continue conducting research and breeding on drought-resistant cultivars. Cereals, and especially wheat, are world's most demanded food, and their climate resilience is critical for global food security.

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Conflict of interest

The authors declare no conflicts of interests.

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References

Abdelhamid MT. 2010. Efficient root system in legume crops to stress environments. Pages 292-242 *in* S. Yadav and R. Redden, editors. Climate Change and Management of Cool Season Grain Legume Crops. Springer, Dordrecht. doi: 10.1007/978-90-481-3709-1_13.

Andersen MK, Hauggaard-Nielsen H, Ambus P, Jensen ES. 2005. Biomass production, symbiotic nitrogen fixation and inorganic N use in dual and tri-component annual intercrops. Plant Soil. 266:273–287. doi:10.1007/s11104-005-0997-1.

Bates D, Mæchler M, Bolker B, Walker S. 2015. Fitting linear mixed-effects models using {lme4}. J Stat Softw. 67:1–48. doi:10.18637/jss.v067.i01.

Beillouin D, Schauberger B, Bastos A, Ciais P, Makowski D. 2020. Impact of extreme weather conditions on European crop production in 2018. Philos Trans R Soc, B. 375:20190510. doi:10.1098/rstb.2019.0510.

Ceglar A, Zampieri M, Toreti A, Dentener F. 2019. Observed northward migration of agro-climate zones in Europe will further accelerate under climate change. Earth's Future. 7:1088–1101. doi:10.1029/2019ef001178.

Chapagain T, Riseman A. 2014. Barley–pea intercropping: effects on land productivity, carbon and nitrogen transformations. Field Crops Res. 166:18–25. doi:10.1016/j.fcr.2014.06.014.

De Costa WAJM, Dennett MD, Ratnaweera U, Nyalemegbe K. 1997. Effects of different water regimes on field-grown determinate and indeterminate faba bean (*Vicia faba* L.). I. Canopy growth and biomass production. Field Crops Res. 49:83–93. doi:10.1016/S0378-4290(96)01059-3.

EUROSTAT. 2020. Agricultural Production - crops [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/Agricultural_production_-_crops#Cereals [Accessed 16 September 2020 2020].

FAO-UNESCO. 1997. Soil Map of the world: revised legend. Wageningen, The Netherlands: IRSIC.

Ghaley BB, Hauggaard-Nielsen H, Høgh-Jensen H, Jensen ES. 2005. Intercropping of wheat and pea as influenced by nitrogen fertilization. Nutr Cycling Agroecosyst. 73:201–212. doi:10.1007/s10705-005-2475-9.

Ghaley BB, Porter JR. 2013. Emergy synthesis of a combined food and energy production system compared to a conventional wheat (*Triticum aestivum*) production system. Ecol Indic. 24:534–542. doi:10.1016/j.ecolind.2012.08.009.

Gollner G, Starz W, Friedel JK. 2019. Crop performance, biological N fixation and pre-crop effect of pea ideotypes in an organic farming system. Nutr Cycling Agroecosyst. 115:391–405. doi:10.1007/s10705-019-10021-4.

Gonzalez-Rizzo S, Laporte P, Crespi M, Frugier F. 2009. Legume root architecture: A peculiar root system. In: T. Beeckman, editor. Root Development. Annu Plant Rev. 37:239–287. doi:10.1002/9781444310023.ch10

Grillakis MG. 2019. Increase in severe and extreme soil moisture droughts for Europe under climate change. Sci Total Environ. 660:1245–1255. doi:10.1016/j.scitotenv.2019.01.001.

Hauggaard-Nielsen H, Jensen ES. 2001. Evaluating pea and barley cultivars for complementarity in intercropping at different levels of soil N availability. Field Crops Res. 72:185–196.

Hauggaard-Nielsen H, Jørnsgaard B, Kinane J, Jensen ES. 2008. Grain legume–cereal intercropping: The practical application of diversity, competition and facilitation in arable and organic cropping systems. Renewable AgricFood Syst. 23:3–12. doi:10.1017/S1742170507002025.

Hossain A, Teixeira da Silva JA, Lozovskaya MV, Zvolinsky VP. 2012. High temperature combined with drought affect rainfed spring wheat and barley in south-eastern Russia: I. Phenology and growth. Saudi J Biol Sci. 19:473–487. doi:10.1016/j.sjbs.2012.07.005.

Hothorn T, Bretz F, Westfall P. 2008. Simultaneous inference in general parametric models. Biom J. 50:346–363. doi:10.1002/bimj.200810425.

Iglesias A, Garrote L, Quiroga S, Moneo M. 2012. A regional comparison of the effects of climate change on agricultural crops in Europe. Clim Change. 112:29–46. doi:10.1007/s10584-011-0338-8.

Jensen ES, Carlsson G, Hauggaard-Nielsen H. 2020. Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: A global-scale analysis. Agronomy for Sustainable Development. 40:5. doi:10.1007/s13593-020-0607-x.

Karpenstein-Machan M, Stuelpnagel R. 2000. Biomass yield and nitrogen fixation of legumes monocropped and intercropped with rye and rotation effects on a subsequent maize crop. Plant Soil. 218:215–232.

Kaye JP, Quemada M. 2017. Using cover crops to mitigate and adapt to climate change. A Review. Agronomy for Sustainable Development. 37:1–17. doi:10.1007/s13593-016-0410-x.

Krogman KK, Hobbs EH, McKenzie RC. 1980. Response of faba bean yield, protein production, and water use to irrigation. Can J Plant Sci. 60:91–96. doi:10.4141/cjps80-013.

Landbrugsstyrelsen. 2020. Vejledning om gødsknings- og harmoniregler. Planperioden 1. August 2020 til 31. juli 2021. (Guide to fertilization and harmony rules. Plan period). Copenhagen, Denmark: Landbrugsstyrelsen.

Lavania D, Siddiqui MH, Al-Whaibi MH, Singh AK, Kumar R, Grover A. 2014. Genetic approaches for breeding heat stress tolerance in faba bean (*Vicia faba* L.). Acta Physiol Plant. 37:1737.

Mäkinen H, Kaseva J, Trnka M, Balek J, Kersebaum KC, Nendel C, Gobin A, Olesen JE, Bindi M, Ferrise R, et al. 2018. Sensitivity of European wheat to extreme weather. Field Crops Res. 222:209–217. doi:10.1016/j.fcr.2017.11.008.

Malézieux E, Crozat Y, Dupraz C, Laurans M, Makowski D, Ozier-Lafontaine H, Rapidel B, de Tourdonnet S, Valantin-Morison M. 2009. Mixing plant species in cropping systems: concepts, tools and models. A Review. Agronomy for Sustainable Development. 29:43–62. doi:10.1051/agro:2007057.

Marino D, Frendo P, Ladrera R, Zabalza A, Puppo A, Arrese-Igor C, González EM. 2007. Nitrogen fixation control under drought stress. Localized or systemic? Plant Physiol. 143:1968–1974. doi:10.1104/pp.107.097139.

Müller U, Grimme K, Meyer C, Ehlers W. 1986. Leaf water potential and stomatal conductance of field-grown faba beans (*Vicia faba* L.) and oats (*Avena sativa* L.). Plant Soil. 93:17–33.

Plies-Balzer E, Kong T, Schubert S, Mengel K. 1995. Effect of water stress on plant growth, nitrogenase activity and nitrogen economy of four different cultivars of *Vicia faba* L. Eur J Agron. 4:167–173. doi:10.1016/S1161-0301(14)80043-9.

Porter JR, Gawith M. 1999. Temperatures and the growth and development of wheat: a review. Eur J Agron. 10:23–36.

Prudent M, Vernoud V, Girodet S, Salon C. 2016. How nitrogen fixation is modulated in response to different water availability levels and during recovery: A structural and functional study at the whole plant level. Plant Soil. 399:1–12. doi:10.1007/s11104-015-2674-3.

R Core Team. 2020. R. A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.

Ray DK, Gerber JS, MacDonald GK, West PC. 2015. Climate variation explains a third of global crop yield variability. Nat Commun. 6:5989. doi:10.1038/ncomms6989.

Rodriguez C, Carlsson G, Englund J-E, Flöhr A, Pelzer E, Jeuffroy M-H, Makowski D, Jensen ES. 2020. Grain legume-cereal intercropping enhances the use of soil-derived and biologically fixed nitrogen in temperate agroecosystems. A meta-analysis. Eur J Agron. 118:126077. doi:10.1016/j.eja.2020.126077.

Sedri MH, Amini A, Golchin A. 2019. Evaluation of nitrogen effects on yield and drought tolerance of rainfed wheat using drought stress indices. J Crop Sci Biotech. 22:235–242.

Senapati N, Stratonovitch P, Paul MJ, Semenov MA. 2019. Drought tolerance during reproductive development is important for increasing wheat yield potential under climate change in Europe. J Exp Bot. 70:2549–2560. doi:10.1093/jxb/ery226.

Sepúlveda-Caamaño M, Gerding M, Vargas M, Moya-Elizondo E, Oyarzúa P, Campos J. 2018. Lentil (*Lens culinaris* L.) growth promoting rhizobacteria and their effect on nodulation in coinoculation with rhizobia. Archiv Agronomy Soil Sci. 64:244–256. doi:10.1080/03650340.2017.1342034.

Serraj R, Sinclair TR, Purcell LC. 1999. Symbiotic N2 fixation response to drought. J Exp Bot. 50:143–155.

Sobkowicz P, Śniady R. 2004. Nitrogen uptake and its efficiency in triticale (*Triticosecale* Witt.) – field beans (*Vicia faba* var. *minor* L.) intercrop. Plant, Soil and Env. 50:500–506.

Stagge JH, Kingston DG, Tallaksen LM, Hannah DM. 2017. Observed drought indices show increasing divergence across Europe. Sci Rep. 7:14045. doi:10.1038/s41598-017-14283-2.

Tarighaleslami M, Zarghammi R, Boojar MMA, Oveysi M. 2012. Effects of drought stress and different nitrogen levels on morphological traits of proline in leafe and protein in corn seed (*Zea mays* L.). American-Eurasian J. Agricult Environ Sc. 12:49–56.

Thompson R, Taylor H. 1982. Prospects for *Vicia faba* L. in Northern Europe. Outlook Agric. 11:127–133. doi:10.1177/003072708201100305.

Trnka M, Hlavinka P, Semenov MA. 2015. Adaptation options for wheat in Europe will be limited by increased adverse weather events under climate change. J R Soc Interface. 12:20150721. doi:10.1098/rsif.2015.0721.

Trnka M, Rötter RP, Ruiz-Ramos M, Kersebaum KC, Olesen JE, Žalud Z, Semenov MA. 2014. Adverse weather conditions for European wheat production will become more frequent with climate change. Nat Clim Change. 4:637–643. doi:10.1038/nclimate2242.

Van den Hoof C, Lambert F. 2016. Mitigation of drought negative effect on ecosystem productivity by vegetation mixing. J. Geophys Res Biogeos. 121:2667–2683.

Vignjevic M, Wang X, Olesen JE, Wollenweber B. 2015. Traits in spring wheat cultivars associated with yield loss caused by a heat stress episode after anthesis. J Agron Crop Sci. 201:32–48. doi:10.1111/jac.12085.

Weaver JE. 1926. Root Development of Field Crops., London, New York: McGraw-Hill Book Company.

Wheeler TR, Craufurd PQ, Ellis RH, Porter JR, Vara Prasad PV. 2000. Temperature variability and the yield of annual crops. Agric Ecosyst Environ. 82:159–167. doi:10.1016/S0167-8809(00)00224-3.

Woods BA, Nielsen HØ, Pedersen AB, Kristofersson D. 2017. Farmers' perceptions of climate change and their likely responses in Danish agriculture. Land Use Policy. 65:109–120. doi:10.1016/j.landusepol.2017.04.007.

Zhang X, Chen S, Sun H, Pei D, Wang Y. 2008. Dry matter, harvest index, grain yield and water use efficiency as affected by water supply in winter wheat. Irrig Sci. 27:1–10. doi:10.1007/s00271-008-0131-2.