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Productivity, light interception and radiation use efficiency of organic and conventional arable cropping systems

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ABSTRACT

How the productivity of crops in organic arable farming may be sustainably increased remains a key issue. We combined measurements of crop yield, total aboveground biomass (AGB) and light interception over a 4-year crop rotation cycle from 2015 to 2018 in a long-term experiment in Denmark with arable organic and conventional cropping systems. These cropping systems comprise one conventional (CGL) and two organic (OGL and OGC) crop rotations, where CGL and OGL had three spring cereal and one grain legume crop (faba bean) in the rotation, and the faba bean was in OGC replaced with grass-clover. All crop rotations were grown with and without the use of cover crops, and the organic systems were grown with and without the manure application. The light interception was calculated from measurements of spectral reflectance, and this allowed the AGB to be decomposed into accumulated intercepted PAR (AIPAR) and radiation use efficiency (RUE).

The conventional cropping system (CGL) had significantly greater AGB, AIPAR and RUE compared with the corresponding organic, grain legume-based system (OGL). AIPAR of the organic grass-clover-based cropping system (OGC) was greater than CGL, although the contrary conclusion was found in AGB and RUE. Across crops, RUE was greatest for cereals and smallest for faba bean and grass-clover. AIPAR was consistently greatest for grass-clover, and both grass-clover and faba bean had smaller variability in AIPAR between years and treatments than the cereal crops. Cover crops significantly increased AGB and AIPAR in the organic cropping systems but not in CGL. RUE was not significantly affected by the inclusion of cover crops. The use of manure in the organic systems increased AGB, AIPAR and RUE. The results show that AIPAR can be higher in organic cropping systems compared with conventional cropping systems, but this is not translated into a greater yield of cereal crops. There is, therefore, a need for novel approaches to management and the use of biomass in organic cropping systems for increasing yields for feed and food, and which sustains soil fertility.

1. Introduction

The global demand for food, bioenergy and biomaterials continues to increase as a result of the increasing world population as well as shifts in consumption patterns (Charles et al., 2014). The continued increase in biomass productivity resulting from optimization of fertilizers, pesticides and irrigation has leveled off in many parts of the world (Pretty and Bharucha, 2014), although other parts of the world still show substantial gaps between potential and actual yields (Schils et al., 2018). The dependency on external inputs of modern, highly productive agricultural systems has caused concern for the environmental impacts and has led to policies and regulations that reduce environmental loadings from nutrients and pesticides (Dalgaard et al., 2014). However, there is still a considerable concern for biodiversity loss and greenhouse gas (GHG) emissions from these systems, partly through the effects of crop and soil management on soil quality (Kopittke et al., 2019).

Organic farming is often considered a more sustainable alternative to conventional agriculture, largely because these systems are less reliant on external chemical inputs (Reganold and Wachter, 2016). However, yields are often lower in organic farming compared with conventional systems in climatic regions of high productivity. Therefore, conversion to organic farming can compromise sustainability given the increasing demands for food and other biomass uses (Tuomisto et al., 2012). The yield gap between organic and conventional systems is often attributed

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to fewer nutrients, in particular nitrogen (N) (Seufert et al., 2012), greater crop losses from pests and diseases (De Ponti et al., 2012), as well as greater weed pressure (Melander et al., 2016), but the yield gap may be narrowed by the use of cover crops and improved fertilization management (Knapp and van der Heijden, 2018). It has thus been stipulated that much of the yield gap between organic and conventional farming systems can be overcome by greater diversification of the cropping systems, including the use of crop rotation and cover crops (Ponisio et al., 2015).

Another benefit of organic agriculture is the potential for higher rates of carbon (C) sequestration in soil compared with conventional production (Gattinger et al., 2012), although this has been challenged given that the rate of sequestration depends on the inputs of C in crop residues and manure (Leifeld, 2012). C sequestration has the potential to offset some of the CO_2 and other GHGs released to the atmosphere, but depends on enhancing the C inputs to soils in above- and belowground plant residues. This may be achieved by growing perennial grass-based crops or including cover crops in arable crop rotations (Lal, 2004). Combining organic farming management with green manure and cover crops can therefore potentially increase soil C content.

Plant biomass is the product of the light intercepted by the plant, and the efficiency with which the light is converted to biomass through photosynthesis (Sinclair and Muchow, 1999; Wu et al., 2016). Increases in yield have primarily come through improvements in the capture of light and other resources such as nutrients and water, as well as through a higher harvest index (Foulkes et al., 2007). According to Wu et al. (2016), there has not been much improvement in the resource use efficiencies of crops, including the radiation use efficiency (RUE). Therefore, much of the needed increases in biomass productivity will potentially have to come from increased capture of light, in particular by extending the active growing season of crops (Manevski et al., 2017).

Biomass production and crop yield in organic and conventional cropping systems are affected by management factors such as the inclusion of cover crops and grass-clover leys in the crop rotation, and the application of fertilizer or manure (Shah et al., 2017). However, knowledge of the causes of the gap in harvestable yield between organic and conventional systems is constrained by the lack of information on how these systems affect total biomass production through light interception and RUE. Changes in cropping systems and management practices to enhance light interception and/or RUE open avenues for increasing productivity of agricultural systems as well as providing biomass inputs for enhancing soil C, without the need for additional external inputs.

In this study, we use four years (2015–2018) of data from a long-term experiment in Denmark from organic and conventional arable cropping systems (Olesen et al., 2000). The experiment commenced in 1997 and focuses on the effects of organic, and since 2005, conventional agricultural management on crop yield, C flows and N dynamics (Hu et al., 2018a; Pandey et al., 2018). The experiment includes the effects of fertilization treatments as well as the use of whole-year green manure crops and cover crops, and the duration of the experiment allows the long-term effects of different cropping systems management to be studied.

The objectives of this study are to quantify how AGB production and its dependency on light interception and RUE in organic and conventional cropping systems are affected by cropping systems design. In particular, we focus on the inclusion of whole-year green manure and cover crops, and on how light interception and RUE may be affected by crop and soil management.

2. Materials and methods

Measurements of crop productivity and light interception were conducted during the four years of the fifth cycle (from 2015 to 2018) in a long-term experiment with organic and conventional arable cropping systems that was initiated in 1997 in Foulum, Denmark (56°30′N, 9°34′E) (Olesen et al., 2000). The clay content in the topsoil (0−25 cm) is 88 g kg^{-1}, and the average soil organic C content in 1996 was 23 g kg^{-1}. The climate of the site is cool temperate with a long-term (1991–2020) annual mean temperature of 8.2 °C and annual precipitation of 674 mm. The annual mean temperature during the experiment varied between 8.5 °C (2017) and 9.2 °C (2018), the total annual precipitation varied between 539 mm (2018) and 854 mm (2015), (Fig. 1).

2.1. Experimental design

The experiment had three factors in a factorial randomized block design with two replicates (blocks), where all four crops of three 4-crop rotations were represented every year (Table 1). The experiment consists of three crop rotations; OGC (organic with grass-clover), OGL (organic with grain legumes) and CGL (conventional with grain legumes). All crop rotations are grown with and without cover crops (+/−CC), and with and without manure (+/− M) in OGC and OGL treatments with cover crops. CGL only included mineral fertilized (+F) treatments. Overall, the incomplete combination of experimental factors resulted in eight treatments: OGC+CC+M, OGC-CC+M, OGC+CC-M, OGL+CC+M, OGL-CC+M, OGL+CC-M, CGL+CC+F, CGL-CC+F. All crops were represented every year for each treatment in two replicates, resulting in 64 plots. The plot size was 12 × 18 m, leaving space for realistic crop management and measurements and monitoring of soil and crops.

When the experiment was initiated in 1997, it consisted only of the two organic crop rotations (OGC and OGL) but changed in 2005 to the three tested rotations shown in Table 1 (Pandey et al., 2018). The treatment combinations have been maintained throughout the experimental period since 2005, and the results measured during 2015–2018 thus reflect long-term treatment effects. The average dates of emergence, anthesis and maturity of the non-grass crops are shown in Supplementary Table S1.

The cover crops in OGL and OGC were a mixture of perennial ryegrass (*Lolium perenne* L.), chicory (*Chicorium intybus* L.), white clover (*Trifolium repens* L.), and red clover (*Trifolium pretense* L.) undersown in May. For CGL, a mixture of perennial ryegrass and chicory was grown as cover crop. All cover crops were sown in May with a seeding density of 10 kg/ha and the cover crops emerged in the first week of June (see Supplementary Table S2 for sowing dates). The cover crops were ploughed into the soil in the following spring before sowing the next main crop.

Manure in the form of pig slurry was applied in the +M treatments in OGC and OGL at the rates shown in Table 1. The rate of mineral N application in CGL was determined by the Danish national standard for fertilizer application to specific crops. The amount of total N applied with manure was scheduled for 70 kg N ha^{-1} as average for the rotation, and this accords with the allowed imported manure of conventional origin to organic farming according to Danish national regulations (Plantedirektoratet, 2005). The manure in OGC and OGL was applied to the cereal crops according to their N requirements, and the slurry was injected into the soil before sowing. The timing of the fertilizer application can be found in Supplementary Table S2.

Weeds were controlled in OGC and OGL rotations by harrowing and inter-row hoeing in spring to regulate annual weeds. Autumn harrowing of plots with perennial weeds was performed in the −CC treatments, and inter-row hoeing of the cover crops was performed in the +CC treatments of OGC and OGL. Weeds, pests and diseases were controlled by pesticides in CGL.

Irrigation was applied once in 2016, adding 15 mm, and four times in 2018 to a total of 145 mm. Irrigation was applied uniformly across the experimental field, and was targeted to minimize yield losses in the cereal crops.

The cereal and grain legume crops were harvested at maturity using a combine harvester. Grass-clover was cut multiple times throughout the growing season; three times in 2015, 2016, and 2017, and four times in

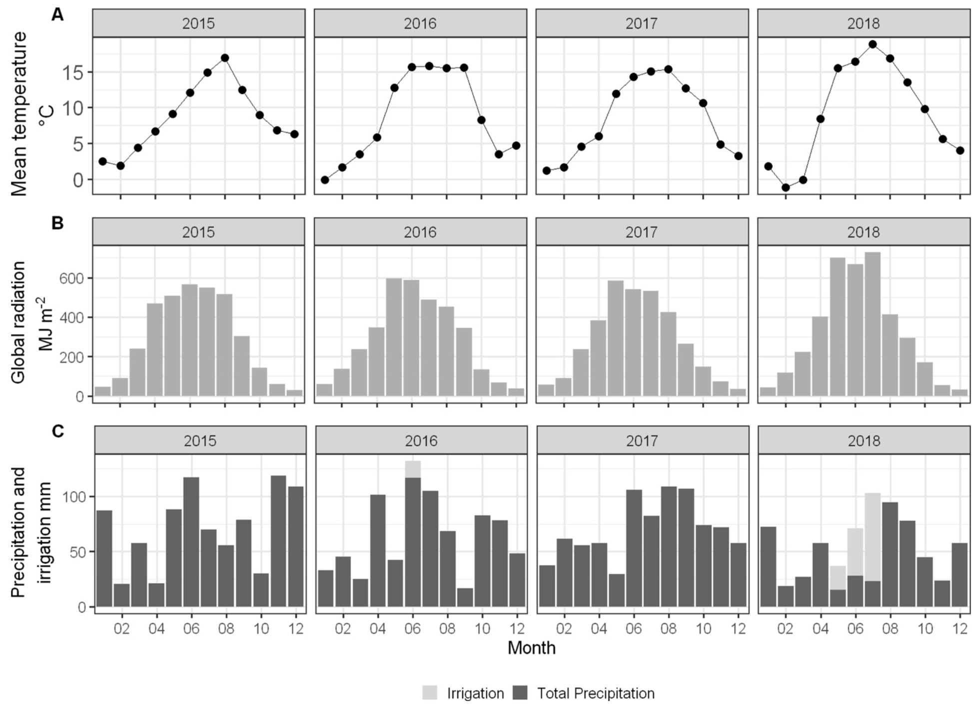

Fig. 1. Monthly mean temperature (°C) (A), monthly total global radiation (MJ m^{-2}) (B) and monthly total precipitation (dark grey) and irrigation (light grey) (mm) (C) for the four years of the experiment period at Foulum.

Table 1
Structure and crop sequence of the 4-year organic (OGC and OGL) and conventional (CGL) cropping systems.

OGC		OGL		CGL	
Crop	Manure (kg N ha^{-1})	Crop	Manure (kg N ha^{-1}).	Crop	Fertilizer (kg N ha^{-1}).
Spring barley: ley	82 (40)	Spring barley^{cc}	82 (40)	Spring barley^{cc}	121 (0)
Grass-clover	0	Faba bean^{cc}	0	Faba bean^{cc}	0
Spring wheat^{cc}	109 (53)	Spring wheat^{cc}	109 (53)	Spring wheat^{cc}	135 (0)
Oat^{cc}	86 (40)	Oat^{cc}	86 (40)	Oat^{cc}	85 (0)

The total-N in manure and fertilizer is shown with the amount of organic N in brackets (kg N ha^{-1} $year^{-1}$). ^{cc} Cover crops grown after the main crop in treatments with cover crops.

2018. The grass-clover in the +M treatments of OGC (i.e. OGC+CC+M and OGC-CC+M) were removed from the field to simulate recycling of the N through the anaerobically digested slurry, whereas the cuttings in OGC+CC-M were retained and mulched on the soil surface (Brozyna et al., 2013).

2.2. Measurements

Reflectances of red light (640–660 nm) and near-infrared (NIR; 790–810 nm) were measured for each plot using a RapidSCAN CS-45 instrument (Holland Scientific, Lincoln, NE, USA) 130 cm above the ground, covering an area of 0.25 m^2 (108 cm by 23 cm). Two measurements were taken across each plot, beginning 1 m from the start of the plot and 0.5 m from the edges of the plot, and ending 1 m from the end of the plot. The two measurements were averaged. The measurements integrated the spatial variation of each plot. Between 15 and 20 measurements were taken each year for each plot, and the time interval between measurements was approximately 7–14 days, with more frequent measurements during late spring and summer.

AGB from each of the cereal and faba bean plot was sampled at least 0.5 m from the edge of the plot at maximum biomass about 1–2 weeks before yellow maturity, for the cover crops and weeds at around November 1st, and for grass-clover one day before each of the cuts and harvests. For each plot, two 0.5 m^2 areas were sampled by cutting plants at 1 cm height above the ground. The cut biomass was dried in the oven at 60 °C for 48 h to a constant weight, to determine dry weight.

Crop yields of cereals and faba bean were determined by harvesting two sub-plots (15 m by 6 m) of each plot using a plot combine harvester. The dry matter content in cereal grains was determined by near-infrared spectroscopy (InfratecTM 1241 Grain Analyzer, Foss A/S). The dry matter content of the faba bean seeds was determined gravimetrically, by weighing before and after oven drying at 60 °C for 48 h.

Daily mean, minimum and maximum temperatures as well as incoming solar radiation were obtained from an on-site meteorological station.

2.3. Calculations

The calculations and statistical analyses were performed in R version 3.6.3 (R Core Team, 2020).

2.3.1. Estimation of the fraction of intercepted photosynthetically active radiation

From the reflectance data collected over the experimental period, the ratio vegetation index (RVI) can be calculated as (Christensen and Goudriaan, 1993):

$$RVI = \frac{\rho_i}{\rho_r} \tag{1}$$

where ρ_i is the NIR reflectance and ρ_r is the red reflectance for each measurement.

Then, using the method of estimating the fraction of intercepted photosynthetically active radiation (fIPAR) from Manevski et al. (2017), fIPAR is calculated as:

$$fIPAR = a + b * RVI^c \tag{2}$$

where the constants a, b, and c are estimated using non-linear regression on a constructed dataset of modeled RVI values that are constructed using Eq. 3, which depends on Eqs. 4 and 5 (Christensen and Goudriaan, 1993):

$$RVI = \frac{\rho_{i,\infty} + (\frac{\eta_i}{\rho_{i,\infty}})(1 - fIPAR)}{\rho_{r,\infty} + (\frac{\eta_r}{\rho_{r,\infty}})(1 - fIPAR)^2} \times \frac{1 + \eta_r(1 - fIPAR)^2}{1 + \eta_i(1 - fIPAR)} \tag{3}$$

$$\eta_r = \frac{\rho_{r,\infty} - \rho_{r,s}}{\rho_{r,s} - \frac{1}{\rho_{r,\infty}}} \tag{4}$$

$$\eta_i = \frac{\rho_{i,\infty} - \rho_{i,s}}{\rho_{i,s} - \frac{1}{\rho_{i,\infty}}} \tag{5}$$

where $\rho_{i,\infty}$ and $\rho_{r,\infty}$ are the reflectance values of NIR and red light at high leaf area index (the highest RVI values) and $\rho_{i,s}$ and $\rho_{r,s}$ are the reflectance values of bare soil (the lowest RVI values). Since NIR and red reflectance are determined not only by the leaf area index of the crop, but also by its greenness (Zhou et al., 2017), the maximum reflectance differed between the grass-clover and the other crops. Thus, two sets of maximum ρ-values were used, representing this variation. The main crop and cover crop were modeled together using the same parameters.

The plots were physically placed across two fields with different long-term history, resulting in different reflectance values for bare soil. To correct this, each of the two fields was assigned a unique set of minimum ρ-values. Having two different maximum ρ-values and two different minimum ρ-values resulted in four different sets of initial data being applied to calculate a, b, and c in Eq. 3 for the respective combinations.

A total of 11 values of fIPAR spaced evenly between [0;1] were used in Eq. 3 as fIPAR for each of the four combinations of ρ-constants, and the corresponding RVI values were calculated. The four sets of a, b, and c in Eq. 2 were then calculated by non-linear regression using nls function in the multcomp package in R (Hothorn et al., 2008), resulting in a formula that allows for the conversion of RVI to fIPAR.

2.3.2. Linear interpolation for daily fIPAR values

Linear interpolation between each date of measurement was performed to calculate the daily fIPAR values. For the first year, there was no information on reflectance for the months before ploughing, which is needed to calculate the PAR intercepted by the cover crops before ploughing. To compensate for this, the average daily fIPAR for each main crop and management combination for the following three years in the period between January 1st and ploughing was calculated and assigned to the days before measuring commenced in 2015.

The daily fIPAR was extrapolated between the last day of measurement in a year until ploughing the next year for each plot, except for 2018 where fIPAR values were extrapolated until the end of the year. The fIPAR value of the last day of measurement in a year was assumed to reflect the average fIPAR in this period. Both temperatures and light were low during this period, and growth therefore also was limited. The impact of fIPAR in the late autumn, winter and early spring on the total accumulated intercepted PAR is thus expected to be quite small regardless of the fIPAR values during this period, see Eq. 6.

2.3.3. Calculation of IPAR

The daily intercepted PAR (IPAR, MJ m^{-2} day^{-1}) was calculated as:

$$IPAR = fIPAR * 0.48 * Q * T \tag{6}$$

where Q is the daily global radiation (MJ m^{-2} day^{-1}), 0.48 converts from global radiation to PAR, and T is a correction factor for the effect of temperature on photosynthetic efficiency (Manevski et al., 2017). T is calculated using Eq. 7, which was determined from Fig. 4e in Wang et al. (2017):

$$T = \begin{cases} 0 \ if \ T_{air} < 4\,^\circ C \\ \frac{-4}{6} + \frac{1}{6} * T_{air} \ if \ T_{air} \in [4\,^\circ\mathrm{C}; 10\,^\circ\mathrm{C}] \\ 1 \ if \ T_{air} > 10\,^\circ C, \end{cases} \tag{7}$$

where T_{air} is the daily mean air temperature (°C).

The total accumulated IPAR (AIPAR) was calculated by cumulating the daily IPAR values for the period needed. AIPAR was calculated for three periods; 1) between ploughing and harvest, corresponding to the growing period of the cereal crops and faba bean, 2) between 1st of January and 31st of December each year, reflecting the growing period for grass-clover, and 3) between 1st of January in 2015 and 31st of December in 2018, which is the whole experimental period and includes cover crops. The AIPAR for the grass-clover does not cover the full period where the grass-clover grows, as it is undersown in the previous main crop of spring barley and is not removed fully until ploughing the following year. The whole period of grass-clover is, however, included in the AIPAR of the full experimental period.

2.3.4. Calculation of RUE

Radiation use efficiency (RUE) for each plot was calculated as:

$$RUE = \frac{AGB}{AIPAR} \tag{8}$$

where AGB is the measured aboveground biomass (g m^{-2}) and AIPAR is the accumulated IPAR (MJ m^{-2}) for the corresponding growing period.

RUE was calculated for each plot using 1) the total AGB for the entire period, including main crops and weeds and cover crops, and AIPAR between 1st of January in 2015 and 31st of December in 2018, 2) the total AGB for the three cereal crops and AIPAR between ploughing and harvest for the years with cereals, and 3) the AGB for all main crops and the AIPAR between ploughing and harvest for cereals and faba bean or 1st of January to 31st of December for grass-clover, used to evaluate the RUE for each main crop each year.

2.3.5. Calculation of harvest index (HI)

The harvest index (HI) was calculated as the harvested yield divided by the AGB of the corresponding crop. Two different estimates of HI were calculated for each plot, total HI and cereal HI. The total HI was calculated as harvested dry matter yield in grain, seeds and grass-clover over the entire 4-year period divided by the cumulated measured above-ground biomass. The cereal HI was calculated as the cumulated cereal dry matter grain yield from the 3 years of cereal crops in the crop rotation divided by the total above-ground biomass measured for the respective cereals.

2.4. Statistical analyses

Statistical analyses were performed using the Analysis of Variance (ANOVA) test with multiple factors and interactions applying Tukey's honestly significant difference test (HSD test) from the "multcomp" package in R version 3.6.3 (Hothorn et al., 2008).

The effect of treatment (in total 8 treatments consisting of combinations of crop rotation (CGL, OGL, OGC), application of fertilizer or manure; (+/- F/M), and presence of cover crops (+/-CC)) on AGB, AIPAR and RUE were analyzed using ANOVA for multiple subsets of the data. Block was included in the model as a factor (Eq. 9). Tukey's HSD was applied to determine which of the treatments were significantly different from each other. The ANOVA thus applied the following statistical model:

$$Dependent\ Variable \sim Treatment + Block \tag{9}$$

where Treatment is the 8 combinations of treatment factors in the experiment.

Additional analyses were conducted on subsets of the dataset to allow for the unbalanced design of the experiment. As in De Notaris et al. (2021), the effect of crop sequence was tested by comparing OGL and OGM (rotation), the effect of organic vs conventional was tested by comparing OGL+M and CGL (system), the effect of cover crops was tested on a subset excluding -M treatments, and the effect of manure (only relevant for OGL and OGM) was tested on a subset excluding -CC treatments. This minimized the possible confounding effects derived by an incomplete factorial design. Also here, a simple ANOVA was used with treatments and block as independent variables.

3. Results

The fIPAR profiles of sample plots from different crop rotations with the same crop entry point were quite similar when the same crop was grown, as illustrated in Fig. 2A. In the autumn and winter period, OGC and OGL with cover crops had higher fIPAR values compared with CGL without cover crops. The fIPAR profiles were also affected by main crop as shown in Fig. 2A for 2018, where the grass-clover in OCG had a higher fIPAR throughout the year and the multiple cuts are detectable as dips in fIPAR throughout the summer period. The IPAR profiles of the sample plots were more similar than the fIPAR profiles (Fig. 2B), since the low incoming radiation and temperature in autumn and winter resulted in low IPAR for all crop rotations.

The AGB, AIPAR and RUE varied between crops and years. Overall, grass-clover had the highest aboveground biomass production and the highest amount of total accumulated IPAR, while the cereal crops had higher RUE compared with faba bean and grass-clover (Fig. 3).

Across management factors, the differences between years for AGB were not significant for most of the years and crops; however, all crops, except spring wheat, had at least one year that was statistically significantly different from others (Fig. 3). There was no pattern as to which year differed from the others across crop species.

The RUE was highest for the cereal crops and lowest for grass-clover (Fig. 3). The RUE was very stable across years for grass-clover, but was significantly lower for faba bean in 2018 compared with the other years. Oat also had the lowest RUE in 2018, whereas the RUE was lowest in 2015 for spring barley and spring wheat.

A comparison of the AGB, AIPAR and RUE for each of the main crops across cropping systems (OGL, OGC, CGL) is shown in the supplementary materials (Fig. S1).

3.1. Crop rotations

There was a strong positive relationship between AIPAR and AGB over the four-year crop rotation cycle across crop rotations and management factors for six of the eight combinations of crop rotation, cover crops, and manure/fertilizer application (Fig. 4).

3.2. Effect of treatments

Overall, cover crops increased AGB and AIPAR over the full rotation cycle (Table 2), likely due to the contribution from cover crop biomass. Across the crop rotations, cover crops on average significantly increased AGB by 13 % and AIPAR by 10 % for fertilized plots. This increase was more prominent for the organic crop rotations with applied manure, with significant increases of 18 % and 14 % for AGB and AIPAR, respectively, and a significant increase of 3 % for RUE. There was no significant difference in AGB and RUE with and without cover crops in CGL, while cover crops significantly increased the total AIPAR by 4 %.

The effect of manure can only be determined for plots with cover crops in the organic crop rotations. For these plots, manure significantly increased AGB and RUE by 10 % and 9 %, respectively, while AIPAR was not significantly affected by manure application.

The positive effect of cover crops on AGB and AIPAR was significantly higher for OGL than for CGL (Table 2), which could reflect a greater N fertilizer value of the legume-based cover crops used in OGL compared with the non-legume cover crops used in CGL (Table 1). In both OGL and CGL, RUE was not affected by the use of cover crops. When cover crops were grown, there was no significant difference in AIPAR between OGL and CGL.

Overall, OGC had significantly higher AGB and AIPAR compared with OGL (Table 2). For plots with manure, cover crops significantly increased AGB by 12 % and 25 % and AIPAR by 6 % and 24 % for OGC and OGL, respectively, and cover crops were, therefore, more effective for increasing AGB and AIPAR in the organic crop rotation with faba bean compared with the rotation with grass-clover, which could reflect the greater proportion of cover crops in OGL compared with OGC. Cover crops increased RUE by 5 % and 1 % for OGC and OGL, respectively.

The fitted model, which includes the effect of treatment combinations is able to explain 83 % of the variability of the total AIPAR of the experimental period, compared with 66 % and 62 % for the total AGB and total RUE respectively.

3.3. Cereal crops

For cereal crops, cover crop significantly increased cereal AGB, AIPAR and RUE by 13 %, 10 % and 2 %, respectively, for organically managed plots (both OGL and OGC) with manure application compared with plots without cover crops (Table 3). Cover crops did not affect cereal AGB, AIPAR or RUE for conventionally managed plots.

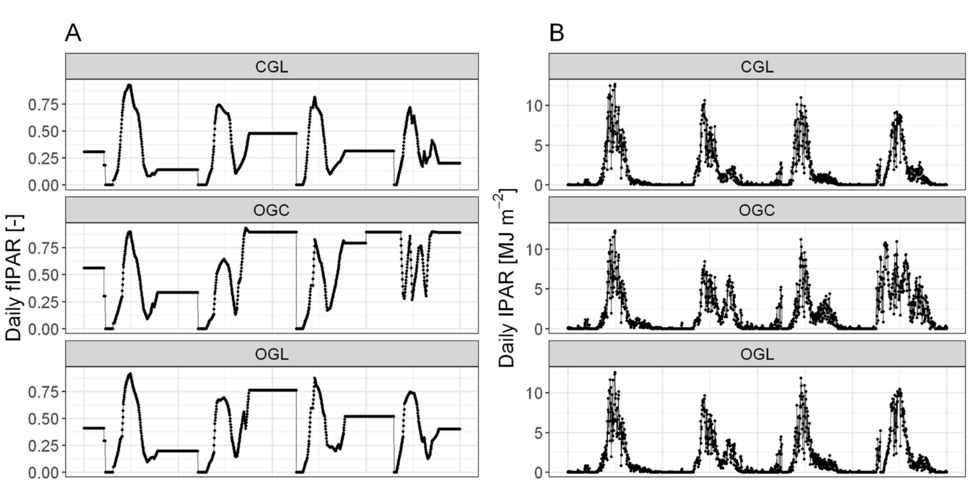

Fig. 2. Examples of calculated daily fIPAR (A) and IPAR (B) values for a plot from each crop rotation illustrating crop and cropping system differences in fIPAR. For all three plots, the crop order is spring wheat in 2015, oat in 2016, spring barley in 2017, and then faba bean for CGL and OGL, and grass-clover for OGC in 2018. The combinations of management factors for the selected plots are from top to bottom: CGL+F-CC, OGL+M+CC and OGC+M+CC. All three plots are from the same block.

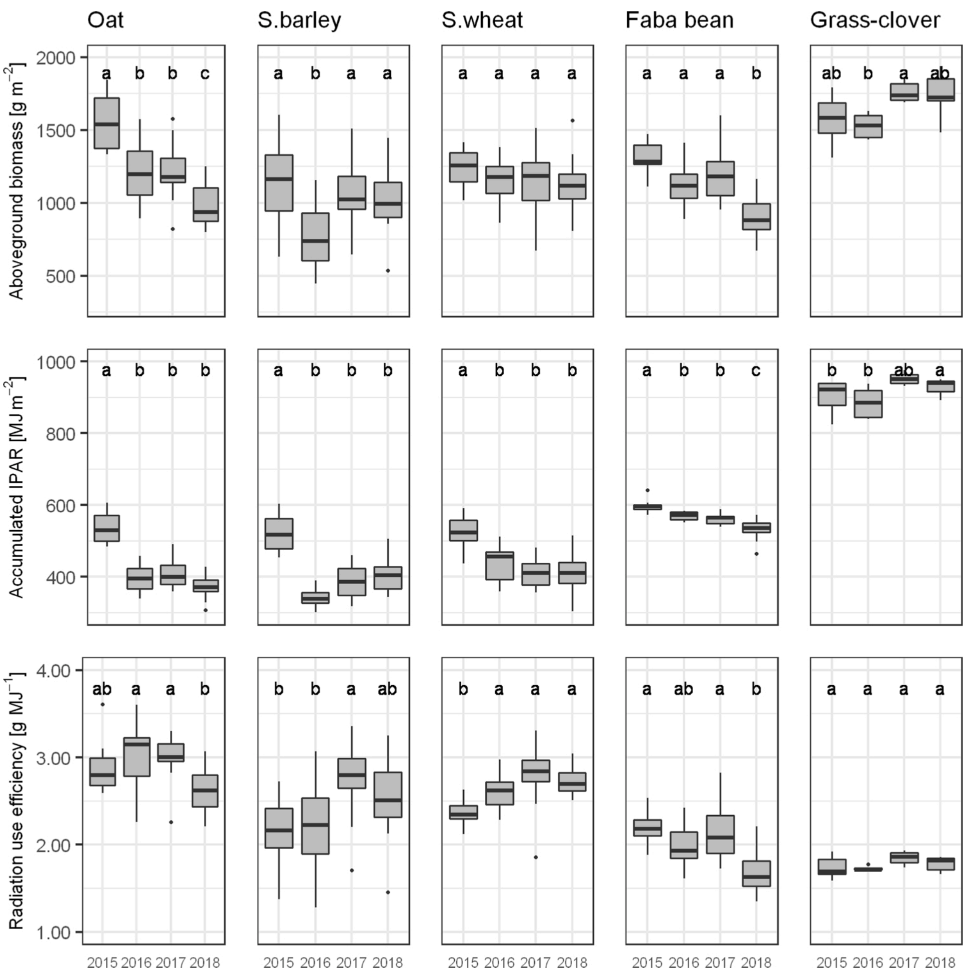

Fig. 3. Aboveground biomass, accumulated IPAR, and radiation use efficiency for the five crops in each year. The data includes all treatments. Letters denote that differences between years are significant (P < 0.05) for each crop. The thick line is the median value of the dataset, the lower and upper boundary of the box is the first and third quartile of the dataset, and dots represent outliers, defined as any point outside 1.5 times the interquartile range, represented by a line. These lines are not symmetrical, as they only extend to the furthest point within this range.

For OGL and OGC, manure significantly increased cereal AGB, AIPAR and RUE for plots with a cover crop, by 15 %, 10 % and 4 %, respectively.

The AGB and AIPAR of the cereal crops were significantly higher in CGL compared with OGL and OGC across management factors. RUE of the cereal crops was significantly higher in CGL compared with OGL, but not for OGC. The cereal AGB, AIPAR and RUE were 22 %, 11 % and 10 % higher, respectively, for CGL compared with OGL with cover crops, and 39 %, 24 % and 12 %, respectively, for CGL compared with OGL without cover crops. Thus, the use of cover crops reduced the gap in cereal AGB and AIPAR between OGL and CGL, whereas RUE was only slightly affected.

With manure application, the cereal AGB, AIPAR and RUE were significantly higher for OGC than OGL. The difference between the two crop rotations when manure was applied, was significantly smaller for cereal AGB and AIPAR when cover crops were included; the differences with cover crops were 7 % and 1 %, respectively, and 11 % and 5 % without cover crops. The cereal RUE was 6 % and 5 % higher for OGC compared to OGL with and without cover crops, respectively, but the difference was not significant, and organic cereal RUE was not affected by cover crops.

The statistical model that includes treatment combinations and block explained more than 70 % of the variation in AGB and IPAR, but only 29 % of the variation in RUE (Table 3).

3.4. Yield and harvest index

The yearly average cereal grain yield was significantly higher for CGL compared with OGL and OGC (Table 4). For treatments with manure or fertilizer applied, the yearly average grain yield was 21 % and 43 % higher for CGL compared with OGL for treatments with and without cover crops, respectively. The total yield, also including faba bean, for the same comparisons were 22 % and 38 % higher, respectively. Cover crops reduced the harvest index for total yield, but with no significant effect on grain harvest index, although the same tendency was present.

The effect of including grass-clover instead of faba bean in the organic crop rotations (OGC compared with OGL) with manure applied was significant for the yearly average total yield, total HI and yearly average cereal grain yield. The yearly average total yield for OGC was 47 % higher than OGL with cover crops and 63 % higher without cover crops, which largely was an effect of including the harvested grass-clover in the total harvested yield for OGC+M. The higher HI of OGC compared with OGL was therefore largely a consequence of the harvested grass-clover. The yearly average cereal grain yield was 5 % and 15 % higher in OGC compared with OGL in systems with and without cover crops, respectively. Thus, the yearly average grain yield difference between OGC and OGL was reduced when cover crops were included in addition to manure. For the systems without manure application, yearly average total yield was lower in OGC compared with OGL, whereas the opposite was the case for yearly average cereal grain yield. In OGC+CC-M the grass-clover was mulched on the soil surface, whereas OGL+CCM includes the faba bean crop that adds to total yield.

The statistical model that includes treatment combinations and block explained about 68–69 % of yield 53 % of the total harvest index and 19 % of the grain harvest index (Table 4).

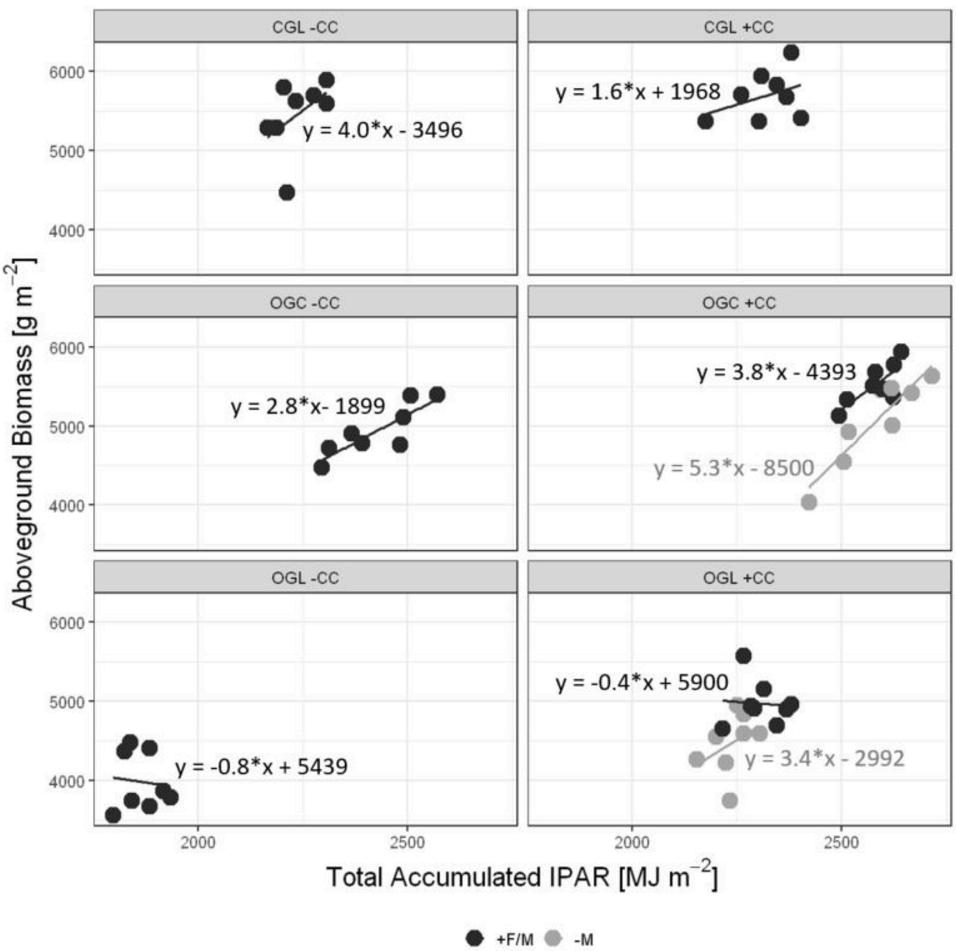

Fig. 4. Total aboveground biomass, including weeds and cover crops, against total accumulated IPAR for each plot over the four-year crop rotation cycle. +F/M signifies the addition of fertilizer or manure on the plots, and -M signifies no addition of manure on the plots. The dots represent one of eight plots in one treatment, one for each main crop (4) present every year in each block (2). The regression lines are simple linear models fit to the plots with the same treatment (crop rotation, +/- CC, +/- M/F).

Table 2
Mean cumulated AGB including cover crops and weeds, AIPAR from 1st of January in 2015 to 31st of December in 2018 and the corresponding RUE for all combinations of experimental treatments.

Crop rotation	Cover crop	Manure/ fertilizer	AGB g m^{-2}	AIPAR MJ m^{-2}	RUE g MJ^{-1}
CGL	+CC	+F	5692 ^{a}	2318 ^{c}	2.46 ^{a}
	-CC	+F	5456 ^{a}	2237 ^{d}	2.44 ^{a}
OGL	+CC	+M	4974 ^{b}	2309 ^{c}	2.16 ^{b}
		–M	4471 ^{c}	2238 ^{d}	2.00 ^{d}
	-CC	+M	3984 ^{d}	1865 ^{e}	2.14 ^{bc}
OGC	+CC	+M	5524 ^{a}	2582 ^{a}	2.14 ^{bc}
		–M	5062 ^{b}	2583 ^{a}	1.96 ^{d}
	-CC	+M	4940 ^{b}	2427 ^{b}	2.03 ^{cd}
R^2			0.657	0.827	0.617

Values within a column with similar letters are not significantly different ($P < 0.05$). The R^2 value is from the linear statistical model described in Section 2.4. The full ANOVA table is shown in Supplementary Table S3.

Table 3
Mean AGB, AIPAR, and RUE for the cereal crops (spring barley, spring wheat and oat) of each crop rotation.

Crop rotation	Cover crop	Manure/ fertilizer	AGB g m^{-2}	AIPAR MJ m^{-2}	RUE g MJ-1
CGL	+CC	+F	4103 ^{a}	1452 ^{a}	2.83 ^{a}
	-CC	+F	4066 ^{a}	1444 ^{a}	2.82 ^{ab}
OGL	+CC	+M	3357 ^{bc}	1312 ^{b}	2.56 ^{cd}
		–M	2859 ^{d}	1151 ^{d}	2.49 ^{d}
	-CC	+M	2923 ^{d}	1166 ^{d}	2.51 ^{d}
OGC	+CC	+M	3501 ^{b}	1329 ^{b}	2.70 ^{abc}
		–M	3192 ^{c}	1252 ^{c}	2.54 ^{cd}
	-CC	+M	3243 ^{c}	1225 ^{c}	2.65 ^{bcd}
R^2			0.725	0.798	0.287

AIPAR was cumulated from ploughing to the harvest of the cereals. The AGB and AIPAR are cumulated values for three years of cereal crops. Values within a column with the same letters are not significantly different ($P < 0.05$). The multiple R^2 values is from the linear model described in Section 2.4.

4. Discussion

4.1. Methodological considerations

The study aimed to explore the factors underlying the productivity of organic arable farming systems by estimating the ability to intercept solar radiation and convert this into biomass. The methodology required the reflectance of bare soil and full vegetation cover. We found that the reflectance of the bare soil varied across the experimental site, and corrected for this. Based on our measurements we also assumed that the reflectance at maximum light interception varied between grass-clover and the other crops. We did not have sufficient measurements to distinguish between other crop types, so we assumed that the values for the main crops also applied to the cover crops, which were modeled as part of the total biomass during the full rotation cycle. Since we used the same instruments for reflectance measurements over all four years, these assumptions are not likely to have influenced the results noticeably.

The measure of biomass in this study is AGB, which means that the belowground biomass is not reflected in the RUE, which would be higher if the belowground biomass was included. The proportion of aboveground biomass to belowground plant parts varies between plant species and depends on crop management (Bolinder et al., 2007). Thus, the

Table 4
Mean yearly dry matter yield and harvest index (HI, yield divided by total aboveground biomass of all crops) across the whole crop rotation (4 years), and dry matter cereal grain yield (spring barley, spring wheat and oats; 3 years) with grain HI calculated as grain yield divided by above ground biomass of the cereal.

Crop rotation	Cover crop	Manure/ Fertilizer	Total yield Mg ha^{-1} year^{-1}	Total HI %	Grain yield Mg ha^{-1} year^{-1}	Grain HI %
CGL	+CC	+F	5.3 ^{b}	41 ^{c}	5.6 ^{a}	41 ^{a}
	-CC	+F	5.7 ^{b}	43 ^{c}	6.0 ^{a}	44 ^{a}
OGL	+CC	+M	4.4 ^{c}	39 ^{c}	4.6 ^{b}	41 ^{a}
		–M	3.8 ^{cd}	39 ^{c}	3.8 ^{c}	40 ^{a}
	-CC	+M	4.1 ^{c}	41 ^{c}	4.2 ^{bc}	43 ^{a}
	+CC	+M	6.5 ^{a}	49 ^{b}	4.8 ^{b}	41 ^{a}
OGC		–M	3.3 ^{d}	28 ^{d}	4.4 ^{bc}	42 ^{a}
	-CC	+M	6.7 ^{a}	54 ^{a}	4.6 ^{b}	44 ^{a}
R^2			0.686	0.525	0.682	0.192

Values within a column with the same letters are not significantly different ($P < 0.05$). The R^2 values is from the linear model described in Section 2.4.

allocation of resources for the aboveground and belowground parts of the plants can be affected by environmental stresses (Hu et al., 2018b), and plants that experience nutrient deficiencies may allocate more resources to the roots (Sippel et al., 2018). Our estimates of RUE will therefore reflect both the efficiency by which radiation is converted to dry matter and how much of this is deposited belowground.

4.2. Variation between years and crops

The weather during the growing season varied considerably between years, with 2017 as particularly wet while 2018 had a record warm and dry summer (Fig. 1). The temperature and precipitation levels in 2015 and 2016 were close to the local average conditions, although still warmer than the long-term average. The conditions in 2015 appear to have been the most ideal for light interception and AGB production for the cereal crops and faba bean, but not for RUE (Fig. 3). Despite irrigation, the effects of the hot and dry year 2018, were seen more in faba bean and oat than the other crops (Fig. 3), suggesting that these species might be more sensitive to drought and heat.

AIPAR for 2015 was significantly higher than for the other years for all crops, except grass-clover (Fig. 3), suggesting that this year had better conditions for annual crops, perhaps due to cooler conditions during springtime extending the growing period (Fig. 1). Similarly, hot and dry conditions as those in 2018 will lead to early maturity and thus lower intercepted radiation of cereal crops, even if irrigation is applied (Webber et al., 2018). The same amount of irrigation was applied to all crops, but this may not have been sufficient for the faba bean crop in 2018, which showed lower AIPAR and RUE than for other years (Fig. 3). The longer growth duration and tall canopy of the oat and faba bean crops give greater water demand than the other cereals and grass-clover, likely resulting in water deficits in 2018, since the same amount of irrigation was applied to all crops.

4.3. Organic vs. conventional farming

Overall, the conventional crop rotation had higher grain yields and higher AGB for both the cereals and whole crop rotation (Tables 2–4) compared with the organic crop rotations for similar management. This difference in performance aligns well with numerous previous findings (Knapp and van der Heijden, 2018; Reganold and Wachter, 2016).

The greater cereal grain yields in conventional compared with organic farming are not caused by higher HI, which was similar across conventional and organic crop rotations (Table 4). Therefore, the greater yield of conventional compared with organic systems are due to both higher RUE and more AIPAR by the crops (Table 3). A comparison of fertilized treatments of CGL and OGL showed that the relative difference in AIPAR was about twice that of the relative difference in RUE. The differences in cereal grain yields between organic and conventional farming were therefore primarily caused by lower interception of global radiation.

There are several underlying factors affecting AIPAR and RUE of the cereal crops in the organic and conventional systems. A comparison of the organic treatments with and without manure shows that manure application increased AIPAR by 13 % and RUE by 5%. Thus, nutrient supply primarily affects AIPAR, and the fact that AIPAR was the main source of the yield difference supports the notion that crop yields in organic farming are primarily constrained by N supply (Berry et al., 2002; Olesen et al., 2007; Pandey et al., 2018). However, plant diseases and pests may also be severely affecting crop yields in organic farming, and such factors would reduce both AIPAR and RUE (Olesen et al., 2000; Schierenbeck et al., 2016).

4.4. Organic systems with grain legumes or grass-clover

Overall, OGC had higher AGB and AIPAR compared with OGL (Table 2), which was expected since grass-clover has a much higher AGB production and intercepts more PAR compared with cereals and grain legumes (Fig. 3). The grass-clover had a lower RUE than the cereal crops and faba bean (Fig. 3). This is mostly related to a greater belowground allocation of biomass in grass-clover than in annual crops, resulting in a buildup of soil carbon in grassland (Hu et al., 2018a; Taghizadeh-Toosi et al., 2020). Faba bean also has relatively high root biomass (Muñoz-Romero et al., 2011), which probably reduced the apparent RUE relative to cereal crops (Fig. 3). Besides, both grass-clover and faba bean have considerable biological N fixation (BNF) (Pandey et al., 2017), and this BNF is energy consuming (Peng et al., 2020), thus reducing the overall RUE of both faba bean and grass-clover.

The large allocation of C and N belowground that can be expected in faba bean and in particular in grass-clover adds fertility to the soil, which results in legacy effects in terms of sustaining N supply for subsequent crops (Pullens et al., 2021). This legacy effect can be seen in the greater AIPAR of cereal crops in OGC compared with OGL (Table 2), whereas these effects were less clear in the cereal grain yields (Table 4), probably because grain yield is also affected by other yield-reducing factors such as diseases and pests.

4.5. Cover crops

Cover crops increased the AGB and AIPAR of the whole organic crop rotation (Table 2) and also of the cereal crops only (Table 3). The effects on the AGB and AIPAR for the entire crop rotation may be partly explained by the additional light interception and growth of the cover crops in autumn as visualized in Fig. 2. However, cover crops also add N fertility to the soil that increases the growth of the cereal crops in the rotation through legacy effects (Pullens et al., 2021). This effect was particularly evident in the AIPAR for the organic cropping systems, whereas AIPAR of the conventional cereals was not affected. This likely reflects the N limitations of the organic cereal crops (OGL and OGC), whereas the fertilization in CGL overshadowed any legacy effects of the cover crops. In addition, the positive effect of cover crops in organic systems can be ascribed to an improved N availability due to reduced N leaching as well as N input via BNF, with the inclusion of legumes in the cover crop mixture (De Notaris et al., 2018, 2021).

The cover crops did not affect the RUE of the entire cropping system or the cereal crops (Tables 2 and 3). However, a slightly smaller proportion of the biomass was harvested in systems with cover crops resulting in a lower total HI (Table 4). This leaves a greater amount of biomass for building soil C and N stocks, which also enhances soil fertility (Abdalla et al., 2019). In addition, C input to the soil via cover crops has been suggested to have a high stabilization potential due to its high quality (Cotrufo et al., 2013; Mortensen et al., 2021). Thus, the inclusion of cover crops in the crop rotation allows for more biomass production and greater soil C input, while potentially increasing the yield of the cereal crops.

4.6. Manure

Manure was only applied in the organic crop rotations, and the manure treatment could only be evaluated in systems with cover crops. Applying manure led to a significant increase in AGB and RUE of the entire system for both OGL and OGC, and a significant increase in AIPAR for OGL (Table 2), while the cereal AGB and AIPAR for both organic rotations were significantly higher for treatments with manure addition (Table 3). These effects are likely related to the enhanced N supply with the manure application (Pullens et al., 2021; Shah et al., 2017). It is notable that cereal AIPAR and AGB in OGL and OGC were similar, in treatments -CC+M and +CC-M (Table 3). This shows that the effect of cover crops equated the effect of manure application, probably the reduced N losses via N leaching in treatments +CC, which allowed more efficient recycling of N in the system, as well as additional N input via BNF thanks to the legume component of the cover crop mixture (De Notaris et al., 2018, 2021). Eventually, cereal grain yield was similar in treatments -CC+M and +CC-M in both OGL and OGC, but greatest in the combined +CC+M treatment (Table 4).

4.7. Perspectives

Increasing the biomass productivity of organic arable cropping systems is paramount for closing the yield gap between organic and conventional systems for contributing to the improved sustainability of these farming systems. However, sustainable cropping systems should also maintain or increase soil fertility, which requires that a significant part of the biomass production in above- or belowground residues be returned to the soil. Our results show that cropping systems primarily vary in AIPAR and less in RUE. Therefore, crop management to enhance crop yields in organic farming will need to focus on enhancing AIPAR through a longer duration of a more effective crop canopy for radiation capture.

The results show that AIPAR in OGC is greater than for CGL. However, the RUE is lower in OGC, and the grass-clover in OGC does not contribute to crop yield. Still, these aspects show that there is scope for increasing overall biomass productivity of organic cropping systems, if some of the biomass produced with the grass-clover and cover crops can be used for feed, fuel or food. Such perspectives may exist with novel biorefining technologies (Parajuli et al., 2015), and further changes in cropping systems and crop management to ensure circularity in the nutrient supply may support this development and contribute to a sustainable increase in productivity.

5. Conclusions

We conclude from the measurements in the long-term crop rotation experiment that crop rotation, cover crops and organic management have a greater effect on AIPAR than on RUE, and this is reflected in changes in AGB, particularly for the cereal crops. AIPAR and RUE are generally higher for the conventional cropping system compared with the two organic cropping systems (OGL and OGC) for the cereal crops. RUE is not significantly affected by manure or cover crops, while it does differ between plant species and to a minor extent between years.

The inclusion of grass-clover in an organic cropping system (OGC) increases the system's AIPAR and AGB, but does not affect RUE when compared with an organic system with a faba bean (OGL). The inclusion of grass-clover does not significantly affect the cereal grain yield. The belowground biomass production might differ between the systems, but this was not assessed in this experiment.

Cover crops do not significantly affect AGB, AIPAR or RUE for the conventional system, while they significantly increase cereal AGB and AIPAR. However, this increase is not reflected in the cereal grain yield. Plots with cover crops have higher potential for building soil C stocks, and thereby enhance soil fertility due to greater biomass production and C input from the cover crops.

CRediT authorship contribution statement

Laura Sofie Harbo: Formal analysis, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Chiara De Notaris:** Investigation, Writing - original draft, Writing - review & editing. **Jin Zhao:** Writing - original draft, Writing - review & editing. **Jørgen E. Olesen:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.eja.2021.126407.

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