DIVERSify: Designing InnoVative plant teams for Ecosystem Resilience and agricultural Sustainability

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Summary report on mechanisms underpinning beneficial plant associations based on APSIM and DAISY (Report, Public)

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Executive Summary

This deliverable reports on the work conducted within WP3, based on two existing crop growth models, APSIM and DAISY. The objective of deliverable 3.1 is to identify the key traits and mechanisms underpinning beneficial plant associations, by calibrating, validating and running APSIM and DAISY. For each model, this report presents in detail i) the data used for model calibration and validation, and the rationale for their choice; ii) the calibration and validation process; iii) the results of simulation runs and comparison with field trial data across pedoclimatic conditions; and iv) a discussion of the key aspects driving the performance of each model and the key plant traits defining the output, with particular reference to intercropped systems. In addition, the report also presents an evaluation of resource use efficiencies in support of the modelling work. On the basis of the calibration and validation results, the two models are also contrasted. APSIM and DAISY showed some promising results for the simulation of spring wheat-faba bean and spring barley-field pea systems, towards the identification of the key traits and mechanisms driving the interaction of cereals and legumes in field conditions and across different pedoclimatic regions. Further steps are discussed towards the improvement of the model capabilities, in particular pertaining intercropped systems, also exploiting some additional experimental results relative to plant nutrient use efficiency.

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1. Introduction

In complex agricultural systems, like intercropped systems, models are powerful tools to go beyond the specific conditions and plant teams considered experimentally, thus considerably extending the range of conditions and plant traits that can be explored. At the same time, for robust results, appropriate model calibration and validation is needed, before models can be run and robust results inferred.

Even models of comparable level of complexity may occasionally lead to substantially different levels of performance. Hence here we calibrate and validate two existing crop growth models, and compare their performances. Specifically, we considered APSIM (Agricultural Production Systems Simulator) (Keating *et al.*, 2003) and DAISY (Ghaley and Porter, 2014; Hansen et al., 1990; Abrahamsen & Hansen, 2000). Both models simulate plant growth and changes in resource availability, based on information on meteorological conditions, soil features, and plant traits. They have been extensively used under different climatic conditions, but more rarely for intercropped systems. The focus of the modelling work was on the cereals and legumes central to most of the DIVERSify field trials, i.e., spring wheat (*Triticum aestivum*) and faba bean (*Vicia faba*), and their intercrop; and spring barley (*Hordeum* vulgare) and field pea (*Pisum sativum*), and their intercrop.

This report is organized as follows. For each model, after presenting in detail the calibration and validation, its performances in monocultures and intercrops are discussed, with particular focus on the key traits and conditions driving the final modelling results and their similarity with the experimental observations collated within DIVERSify. Steps for improvements are discussed. The results of the two models are then contrasted, to identify general patterns, with particular focus on key traits and mechanisms driving the interactions of the focal cereal and legume crops.

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2. Evaluation of APSIM model simulations

APSIM (Agricultural Production Systems sIMulator) is a modular framework to simulate agricultural production systems (Keating *et al.*, 2003). It is capable of simulating a large number of crop species grown under a wide variety of climates and soil types in monocultures. The simulation of the growth of these crops is implemented in crop modules. These crop modules include the crop modules relative to the focal species for DIVERSify: APSIM Wheat, APSIM Barley, APSIM Fababean and APSIM Field pea. These modules are the ones used in this study to simulate crop growth. An additional interesting module of APSIM is the Canopy module, that allows APSIM to simulate intercropping systems (Carberry *et al.*, 1996), which was used to simulate intercrops of spring wheat and faba bean and of spring barley and field pea. The work with the APSIM model simulation summarized in this chapter will be published in a scientific journal (Berghuijs et al. manuscript in prep.).

2.1. Model calibration and validation: datasets used and procedure

For soil data, we used the SoilWat module (Probert *et al.*, 1998) to simulate soil moisture dynamics and the SoilN module (Probert *et al.*, 1998) to simulate the dynamics of carbon and nitrogen in the soil. Meteorological data were collected from various sources, including local weather stations and the ECA (European Climate Assessment) dataset (European Climate Assessment & Dataset: https://www.ecad.eu/dailydata/index.php).

For crop data, we employed two types of experimental data: previously published data and data collected within DIVERSify. The previously published data consisted of detailed measurements on monocultures of spring wheat (Gou *et al.*, 2016), spring barley (Yin *et al.*, 1999), and faba bean (Kropff, 1989; Boons-Prins *et al.*, 1993) from the Netherlands; and spring barley (Corre-Hellou *et al.*, 2006; Corre-Hellou *et al.*, 2007; Corre-Hellou *et al.*, 2009) and field pea (Béasse *et al.*, 2000; Corre-Hellou *et al.*, 2006; Corre-Hellou *et al.*, 2007; Corre-Hellou *et al.*, 2009) from France. These datasets have in common that they provide also within season data on Leaf Area Index (LAI) and total aboveground biomass. The unpublished DIVERSify data contain both monocultures and intercrops collected at various locations in Europe, and all trials followed a similar design as the field trial in the UK described by Karley et al. (2018). So far, only the 2017 DIVERSify data were used, because the 2018 data were not available yet at the time of this work.

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2.2. Results of model calibrations, validation and simulations (monocultures and intercrops)

For the calibration and validation of APSIM Wheat, we used within-season data from Wageningen (the Netherlands) on spring wheat phenology, dry matter and its partitioning, LAI, and yield components from the experiment described by Gou *et al.* (2016). Figure 1 shows an example of the comparison between simulated and dry weights and leaf area indices for both the calibration and the validation dataset.

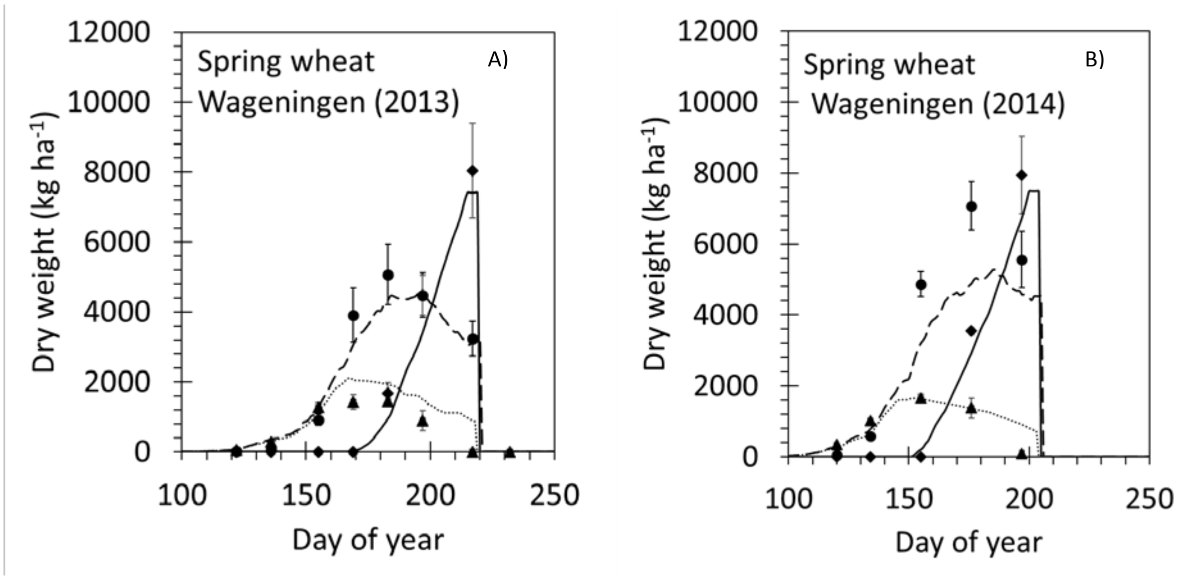

Figure 1: *Simulated and measured biomass partitioning in spring wheat for the experiments from Gou et al. (2016). Measured ear, stem and leaf biomass are represented as diamonds, dots, and triangles respectively. Simulated head, stem and leaf biomass are represented as solid lines, dashed lines, and dotted lines, respectively. The length of an error bar is one standard deviation.*

To calibrate APSIM Barley, we used within season data from Wageningen (the Netherlands) on spring barley phenology, dry matter and its partitioning, LAI, and yield components from the experiment described by Yin *et al.* (1999). Figure 2 shows an example of the comparison between the calibration data and the simulated values.

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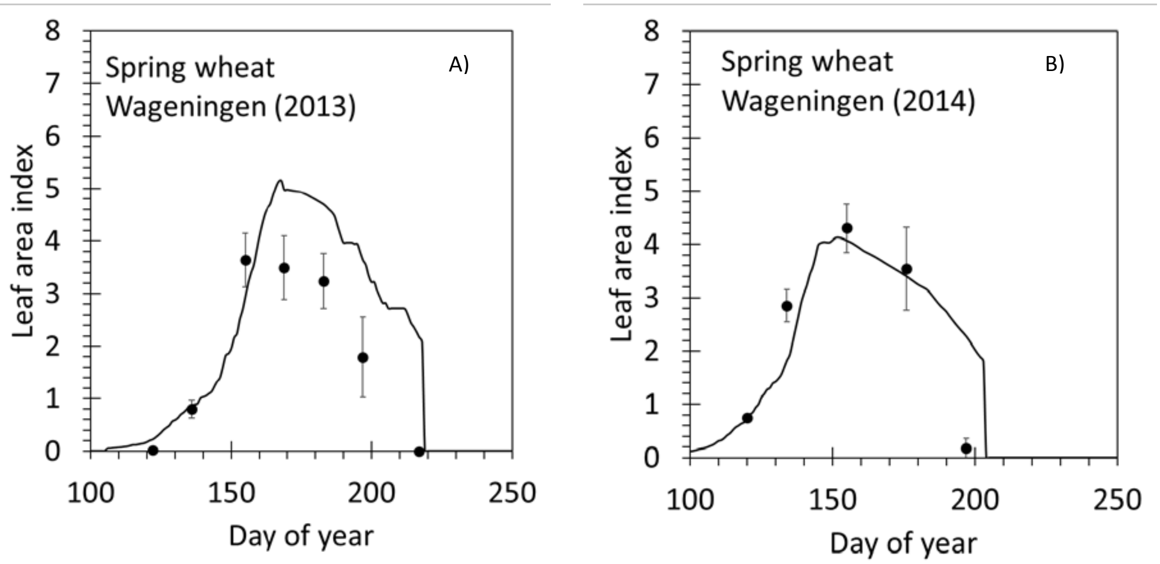

Figure 2: *Simulated and measured leaf area indices in spring wheat for the experiments from Gou et al. (2016). Dots represent measurements and lines simulated values. The length of an error bar is one standard deviation.*

For the calibration of APSIM Fieldpea, we used within season data from the experiments conducted in Le Rheu (France) described by Béasse *et al.* (2000) on pea phenology, aboveground dry matter, and LAI. For validation of the newly calibrated version of APSIM Field pea, we used the monoculture treatments from the experiments that were conducted in Angers (France) and described by Corre-Hellou *et al*. (2006, 2007, 2008). Figure 3 shows an example for the comparison between simulated and measured aboveground dry matter and LAI.

To calibrate APSIM Fababean, we used within season data from the experiments described by Kropff (1989) (only 1985) and Boons-Prins *et al.* (1993) on faba bean phenology, dry matter and its partitioning, and LAI (not shown). The default APSIM cultivar Fjord (Turpin *et al.*, 2003) was used as the starting point of the calibration.

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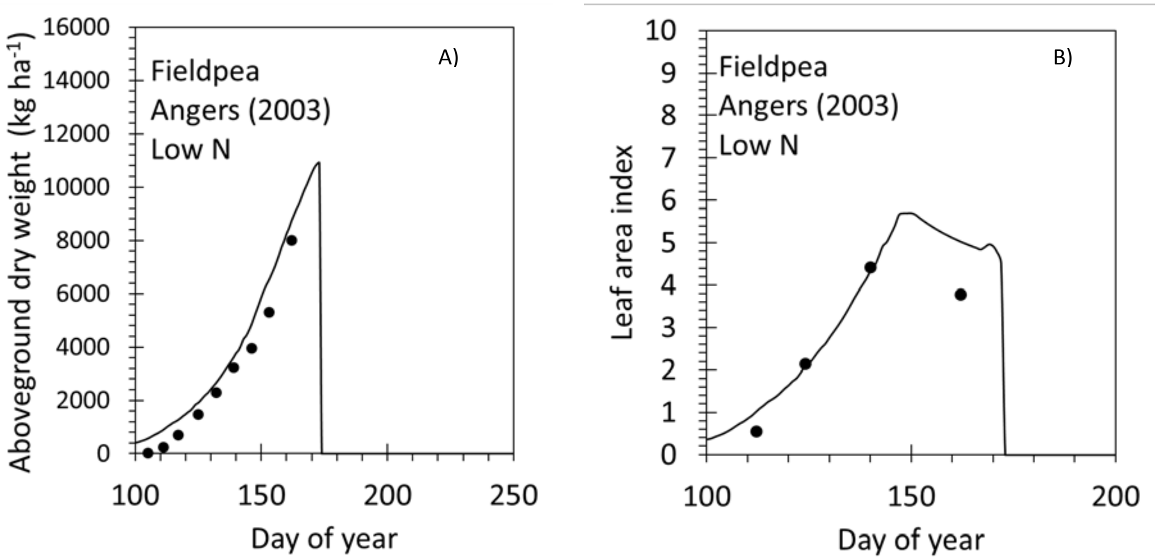

Figure 3: *Simulated and measured field pea aboveground dry matter (A) and leaf area index (B) in the monoculture treatment grown in 2003 under unfertlized conditions from the experiment described by Corre-Hellou et al. (2006,2007,2009).*

The newly calibrated crop modules APSIM Wheat, APSIM Barley, APSIM Fababean and APSIM Fieldpea were used to simulate the grain yields in the DIVERSify experiments conducted in the United Kingdom, Sweden, Denmark, Germany, Austria, and Italy (only data from 2017 and datasets containing monocultures were considered). Figure 4 presents an example for measured and simulated yields in the monocultures, and Figure 5 shows measured and simulated yield of each crop species in either a wheat-faba bean or a barley-pea intercrop.

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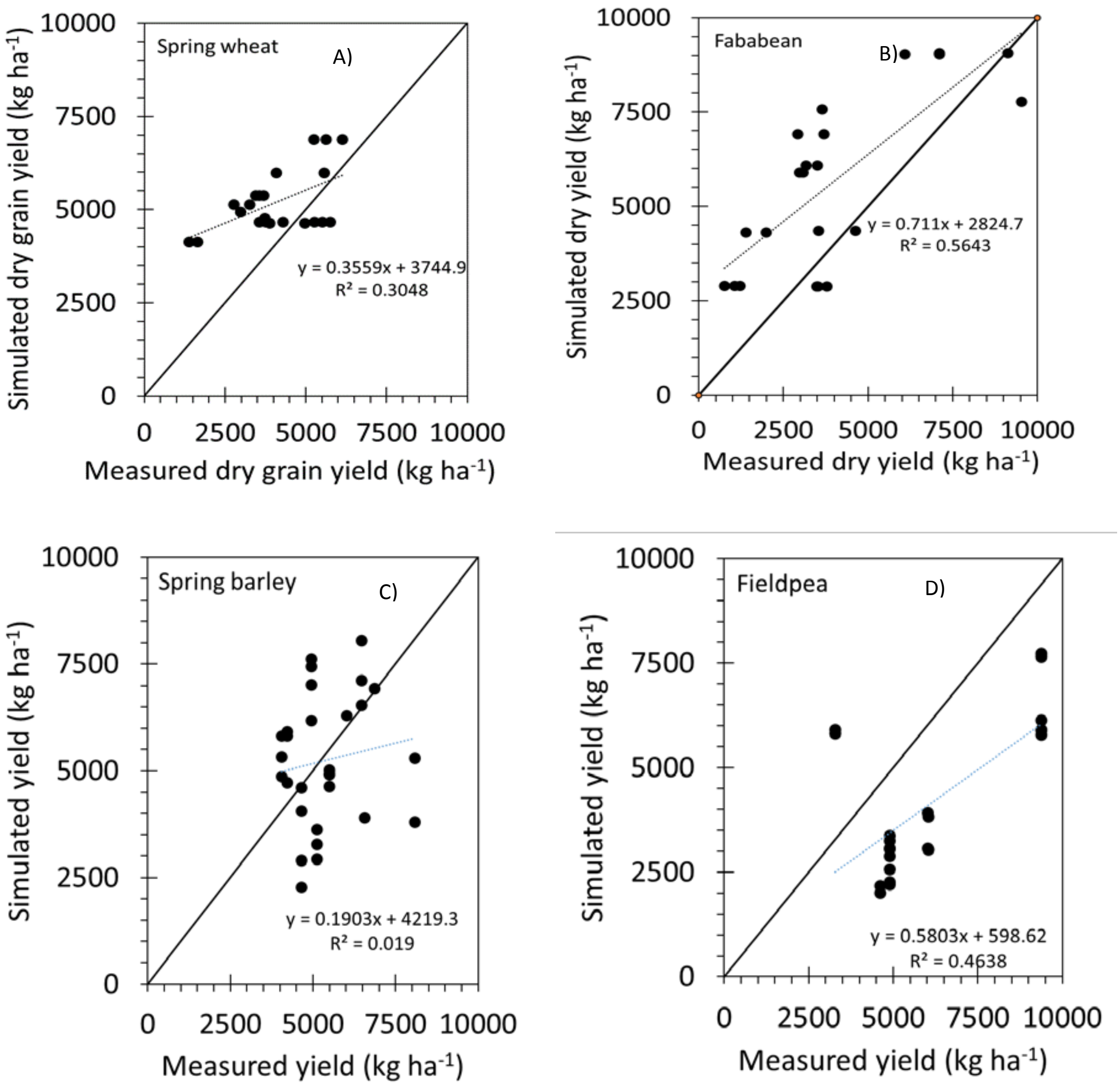

Figure 4: *Comparison between simulated and measured grain dry matter in the DIVERSify field trials for spring wheat (A), faba bean (B), spring barley (C), and field pea (D) grown as monocultures. The solid lines represent the one-to-one relationship. The dotted lines represent fitted linear regression models.*

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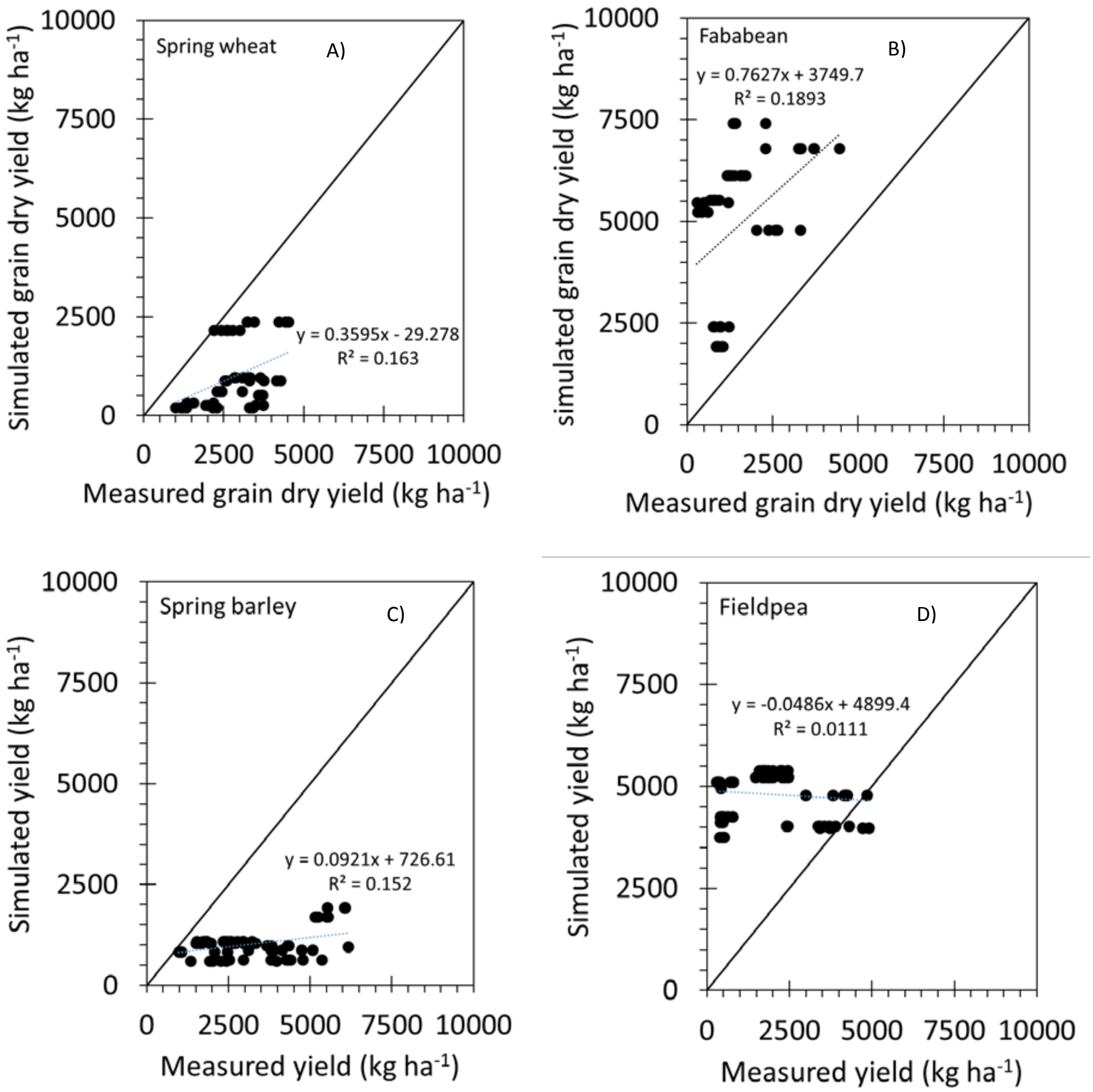

Figure 5: *Comparison between simulated and measured grain dry matter in the DIVERSify field trials for spring wheat (A), faba bean (B), spring barley (C), and field pea (D) grown as wheat-faba bean intercrops (A-B) or barley-pea intercrops (C-D). The solid lines represent the one-to-one relationship. The dotted lines represent fitted linear regression models.*

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2.3. Discussion of APSIM model suitability for evaluating mechanisms underpinning beneficial plant associations

In this study, APSIM was calibrated and validated with data collected in two locations across Europe and then compared with the DIVERSify data relative to a variety of pedoclimatic conditions. Previously, APSIM had been calibrated and validated only in few studies conducted in Europe; even fewer studies considered intercropping. Specifically, APSIM Wheat had only been validated in two studies in Europe (Asseng *et al.*, 2000; Knörzer *et al.*, 2011), APSIM Fieldpea in one (Knörzer *et al.*, 2011). To our best knowledge, APSIM Fababean had never been used in Europe before. APSIM Barley was calibrated and validated once in Europe and it was shown that it underestimated the grain yield (Salo *et al.*, 2016). APSIM had only been used in a single European intercropping study, in which a wheat-field pea system was simulated (Knörzer *et al.*, 2011). In that study, APSIM underestimated the yield and the aboveground biomass of field pea, when it was grown in an intercropping system. We also found in preliminary simulations that APSIM tends to underestimate the grain yields for each of the crop investigated, if we would have used default cultivars defined in APSIM for our simulations. Hence, in order to use APSIM to design sustainable cropping systems in Europe, additional calibration and validation of APSIM in European production systems was necessary. Hence, we first recalibrated and validated the crop modules APSIM Wheat, APSIM Barley, APSIM Fababean, and APSIM Field pea on well fertilized trials in the Netherlands (Kropff, 1989; Yin *et al.*, 1999; Gou *et al.*, 2016) and France (Béasse *et al.*, 2000; Corre-Hellou *et al.*, 2006; Corre-Hellou *et al.*, 2007; Corre-Hellou *et al.*, 2009).

We chose to calibrate the APSIM crop modules on previously published data, because the DIVERSify dataset was not fully suitable for this task. The most important reason for this is that there were no within-season measurements of biomass and LAI available for many locations. Without within-season measurements, it is not possible to identify model parameters that need to be readjusted if there is a mismatch between simulated and observed final yields and biomass. Another important reason why the DIVERSify dataset was not suitable to calibrate APSIM is that it often lacked measurements of available nitrogen at most locations; these measurements were only available for the field trials conducted in Denmark and Sweden. A third factor that made it hard to use the DIVERSify dataset for calibration was that several DIVERSify trials did not include a fertilized treatment or the fertilized treatment had a fertilization level that was considerably lower than the corresponding amount that would have been added in a conventional monoculture. Therefore for these fields, in practice, there was no control treatment available showing how a monoculture of a cereal would have grown if it did not suffer from nitrogen deficit. If we would have used these data to calibrate APSIM, we would have been forced to take nitrogen

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stress into account for these fields, which considerably increases the number of parameters that potentially need to be re-estimated.

The crop modules APSIM Wheat, APSIM Barley, APSIM Fababean, and APSIM Fieldpea were successfully calibrated and validated based on monoculture data from well-fertilized trials in the Netherlands (Kropff, 1989; Yin *et al.*, 1999; Gou *et al.*, 2016) and France (Béasse *et al.*, 2000; Corre-Hellou *et al.*, 2006; Corre-Hellou *et al.*, 2007; Corre-Hellou *et al.*, 2009). There was a reasonable agreement between the simulated and measured yields in the validation dataset on well fertilized fields for both cereals and legumes in monoculture: spring wheat (Figs 1B, 2B), and field pea (Fig 3), spring barley and faba bean (not shown). There was also good agreement between measured and simulated total aboveground biomass and LAI for field pea monocultures grown under unfertilized conditions, whereas APSIM Barley tended to overestimate the LAI and the total aboveground biomass of spring barley monocultures.

When compared with the monoculture data from the DIVERSify trials, the newly calibrated crop modules APSIM Wheat, APSIM Fababean, and APSIM Fieldpea were able to explain a substantial amount of the variation in monocultures (Fig. 4), which is reflected in correlation coefficients of 0.30, 0.46, and 0.56 respectively. However, APSIM Fababean and APSIM Fieldpea tended to overestimate the yields. APSIM Barley was not capable of explaining the observed variation in yield data (correlation coefficient: 0.02). So far, we were not able to detect the cause of this mismatch between measured and simulated data directly. However, the results of the previously described validation of APSIM Barley indicate that APSIM Barley underestimates the growth reduction of barley due to nitrogen stress. In future research we intend to examine whether the possible underestimation of nitrogen-limited growth can explain the moderate performance of APSIM when simulating the yield of monocultures or whether other factors may explain this mismatch.

We also used APSIM to simulate the grain yields of intercrops included in the DIVERSify trials – spring wheat and faba bean, and barley and field pea. The proportions of variation that could be explained by the model were lower for spring wheat, faba bean and pea in intercrops than in monocultures. The variation explained was higher for barley in monoculture than for intercropped barley, but it was still unsatisfactory ($r^2 = 0.15$). Additionally, the cereal yields were substantially underestimated and the legume yields were substantially overestimated. This suggests that APSIM overestimates the competitive ability of legumes relative to cereals, and that this model does not account for any interaction effects between plants. This observation cannot be explained by our previous finding that APSIM may underestimate the effect of nitrogen shortage on the growth of barley, because this would be expected to make cereals more competitive relative to legumes. More likely explanations are that, in an intercropping situation, the height increase of the cereals is underestimated or that the height

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increase of the legumes is overestimated, or a combination of the two; an effect which could be caused by plant-plant interaction that is not accounted for by APSIM. Another factor that might explain the overestimation of the competitive ability of the legumes could be that the radiation use efficiency was too high for the legumes or too low for the cereals. In future research, we intend to investigate how the mismatch between observed and simulated competitive abilities can be explained.

3. Evaluation of DAISY model simulations

DAISY is a dynamic soil-plant-atmosphere system model for agro-ecosystems. It simulates plant growth and soil processes based on the input of weather data (temperature, precipitation, global radiation and evapotranspiration), soil data (sand, silt and clay content, Carbon (C): nitrogen (N) ratio, bulk density and soil organic matter content), hydraulic parameters, location of ground water and management information (Hansen et al., 1990; Abrahamsen & Hansen, 2000). Management data required for the model are crop rotation, tillage, use of fertilizer and manure, irrigation, sowing and harvesting. The model simulates water, heat, carbon and nitrogen flows at field scale and provides information on crop productivity and nutrient and water dynamics, as a result of management and weather conditions at a particular site of interest. The original DAISY model had not been developed to cope with intercropping situations (Hansen et al., 1990), but was later modified for some intercrops to simulate dry matter in leaf, stem, storage organs and roots (Abrahamsen & Hansen, 2000). For new intercrop combinations to DAISY, like pea-barley used in this study, this setup can be seen as a starting point for testing the model on this intercrop system and for further model calibration and validation.

3.1. Model calibration and validation: datasets used and procedure

For calibration, we used data from a field experiment in 2017 on spring barley monoculture (or barley sole crop, BSC), pea monoculture (or pea sole crop, PSC) and pea-spring barley intercrop (IC). The experimental field was located at the Experimental Farm in Taastrup, Denmark. Before sowing, soil was sampled from 0-75 cm depth in four replicates and analyzed. The soil N supply was 18 kg N ha^{-1} with 1.57 mg NO_3-N and 0.1 mg NH_4-N kg^{-1} soil. The year before the trial in 2016, the experimental site was cultivated with malting barley and conventional management practice was followed (documented in the field trial record of the experimental farm). Prior to sowing in 2017, Biogrow (NPK 10-3-1), an organic fertilizer, was applied at the rate of 12 kg N ha^{-1}, to the field. Spring barley (cv. Salome) and pea (cv. Mythic) were sown as monocultures and as intercrops in 50:50 ratio in same rows. Both monoculture and intercrop plots were divided into two treatments; 0 kg N ha^{-1} (N0) and 100 kg N ha^{-1}

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(N100). N100 was applied in two doses each of 50 kg N ha^{-1} in the form of urea at 30 and 67 days after emergence (DAE). Sampling of biomass for dry matter (DM) and N content analysis were carried out at 30, 67 and 102 DAE on 31st May, 7th July and 11th August 2017 respectively for the N100 plots, while DM and N content were recorded for N0 plots at harvest. Grain yields were measured at harvest corresponding to 102 DAE. The soil data used are soil texture and horizons, hydraulic properties, and parameterized denitrification rate. Calibrated soil parameters were taken from a previous study carried out at the experimental farm. The weather data is from the local weather station at Taastrup Campus, located within the experimental farm, approximately 130 m from the experimental field. Spring barley and pea crop input data parameterized for growing conditions and yield targets in Denmark was used. The field was under conventional management for the past four decades.

DAISY simulations are influenced by the initial distribution of soil organic matter (SOM) and changes in management at the site before the onset of the simulated experiment (Bruun & Jensen, 2002). The initial distribution of SOM is dependent on the specific field conditions and previous management, but was unknown for this experiment. The N mineralization measured before the beginning of the trial at 18 kg N ha^{-1} is sensitive to time of year with respect to weather conditions and management. DAISY defines soil organic matter as an entity that cannot be directly measured and hence the distribution of SOM cannot be initialized by a simple measurement (Bruun & Jensen, 2002). The most reliable way of calibrating was therefore to compare a model output (e.g. total crop N) with measured data of the same parameter. The model was initialized with two SOM fractions, a fast and a slow fraction. The percentages of each of the SOM fractions were altered until the simulated total crop N at harvest time matched with the measured data for the N0 and N100 treatments. The same method has been used by Manevski et al. (2016). When simulating intercropping, LAI was very high for the pea and low for the barley compared to the LAI typical of Danish growth environments. Similar to the observations with APSIM, this resulted in low yields of the barley in intercrops as the pea component out-competed the barley component in the simulation. Hence, the height of the pea was adjusted in the model parameter that was used to simulate height corresponding to development stage (DS) of pea. The pea height was changed to 50 cm at DS1 (flowering) and DS (ripe) from the default settings for monoculture pea at 100 cm. The 50 cm height corresponded well to the heights of the Mythic pea variety used in this experiment with plant heights of 45-55 cm. Further details of the calibration and validation procedure are documented by Ghaley and Hansen (2019), which is found in Appendix 1.

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3.2. Results of model calibrations, validation and simulations (monocultures and intercrops)

Calibration was performed in two steps, starting with the soil organic matter (SOM) followed by pea plant height. For barley monoculture at N100 fertilization, the SOM model simulations of total crop N and total DM at 30 and 67 days after emergence fit quite well to the measured values (Figure 6). At harvest, the model overestimated the total crop N of the BSC in the N100 treatment. For the unfertilized plot with N0, the simulated total crop N was slightly underestimated. The model fit will be improved with further calibration.

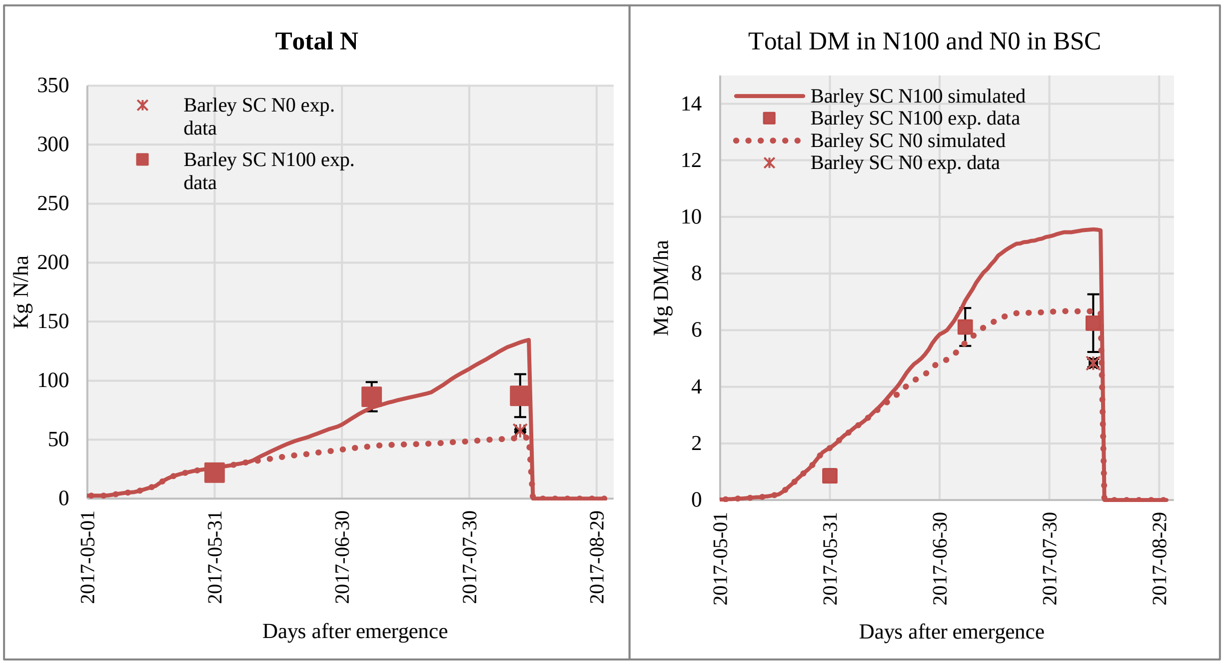

Figure 6. *Total N and total DM for spring barley monoculture (or sole crop). Simulation compared with measurements at 30, 67 and 102 DAE (31st May, 7th July and 11th August 2017) for N100 and at 102 DAE for N0.*

The pea height simulations at N100 overestimated the total pea monoculture N content compared with the measured data at 67 and 102 DAE (Figure 7). The total DM fitted quite well the measured data except at 102 DAE. There was little variation in the PSC simulations between N100 and N0.

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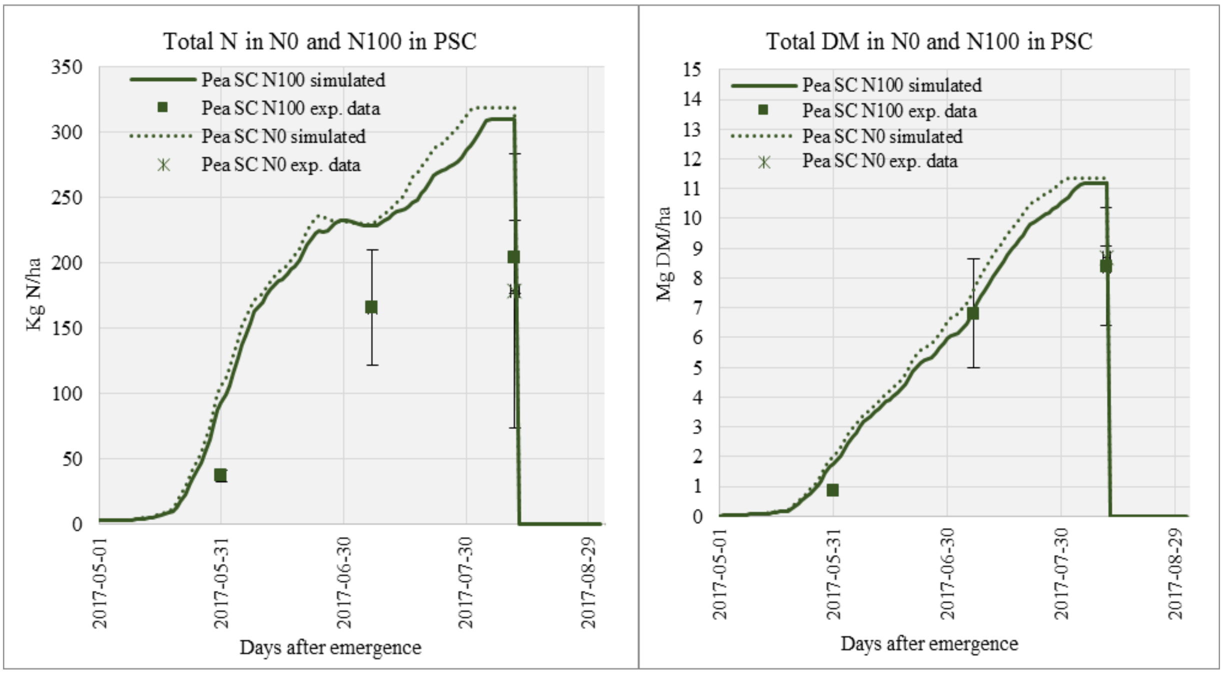

Figure 7. *Total N and total DM for pea monoculture (or sole crop). Simulation compared with measurements at 30, 67 and 102 DAE (31st May, 7th July and 11th August 2017) for N100 and at 102 DAE for N0.*

The intercrop simulations for N100 resulted in a good fit for the barley component only at the beginning of the growing season, but the measured data shows a larger increase in total N in July and then a decrease at final harvest, whereas the simulation shows a steep increase at the end of the growing season (Figure 8). The total crop N was linked to the difference in N fixation in the pea in N100 and N0 treatments. Thus, the PSC fixed 200.8 kg N/ha in N0 and a reduced quantity of 143.9 kg N/ha in N100 (see Ghaley and Hansen, 2019; Appendix 1). In the intercrop, barley took up the bulk of the soil nitrogen and the intercropped pea was forced to meet the N requirement through fixation. The increase in N fixation in cereal-legume intercrops has been recorded in other studies (Hauggard-Nielsen et al., 2009).

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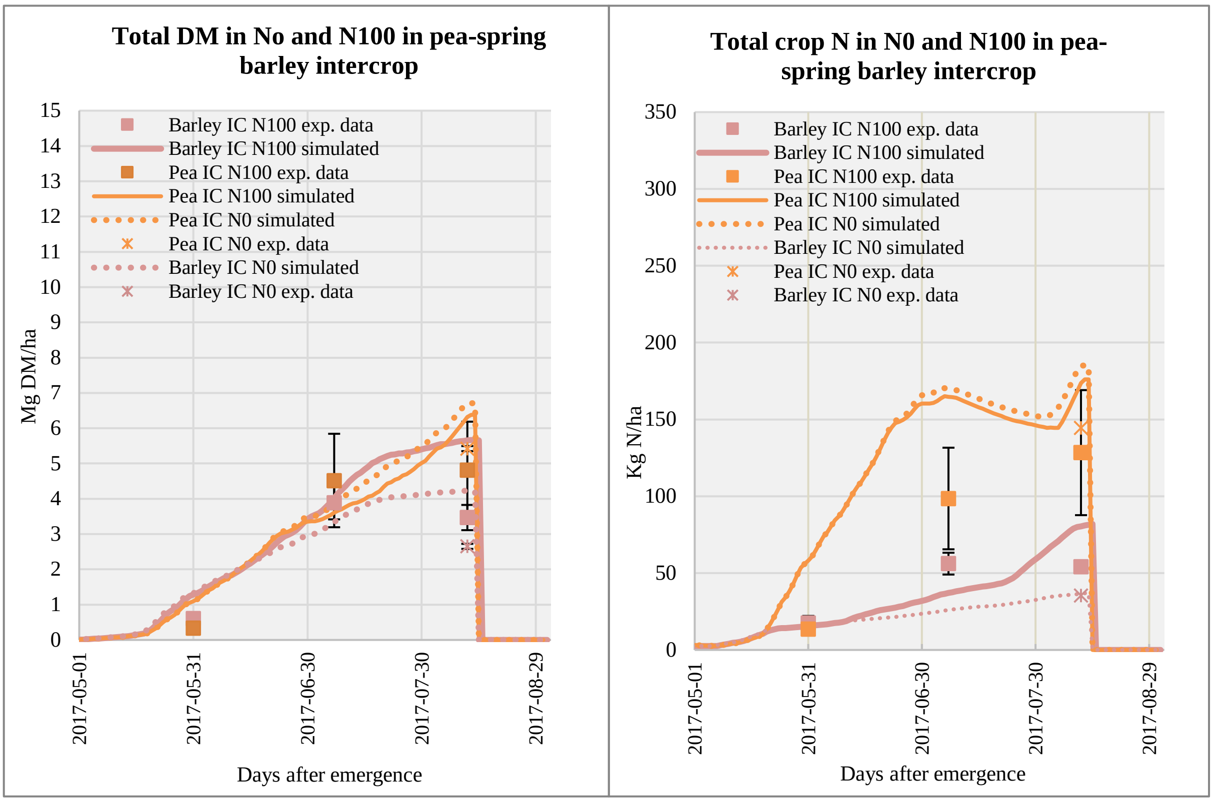

Figure 8. *Total N and total DM for intercropping. Simulation compared with measurements at 30, 67 and 102 DAE (31st May, 7th July and 11th August 2017) for N100 and at 102 DAE for N0.*

After the calibration, for the validation of the model setup in a long-term scenario accommodating temporal changes in SOM and soil N, we simulated an organic 11 year crop rotation (2005-2016) including wheat, barley and pea, though not intercropped. The model simulations were compared to the yields. The management was set to default management in accordance to Danish standard practices for organic farming without fertilizer. The 2005-2016 simulation results show that simulated yields for pea and spring barley underestimated the measured values but were significantly correlated (Figure 9).

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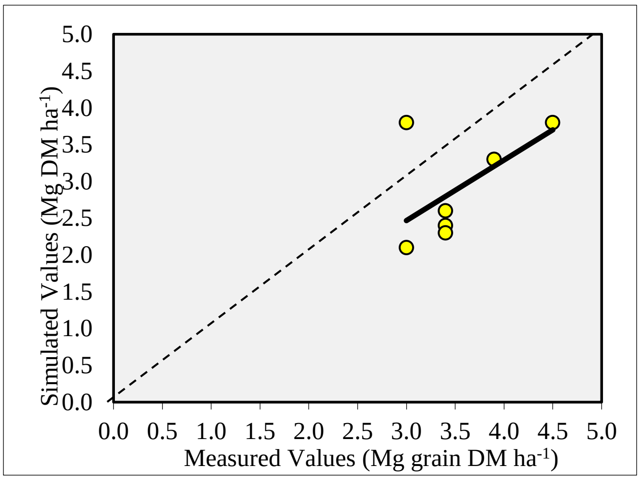

Figure 9. *Correlation between measured yield data from 2005-2016 (long-term yield data and simulated BSC and PSC). R^2=0.94. Significant at P ≤ 0.05**

Prior to 2005, two years of clover were simulated to create realistic initial conditions as clover is regularly grown on these fields, as per the crop rotation. For the spring wheat grown in 2006 and 2010, an input of 50 kg N/ha was assumed in the simulation to account for N2-fixation by cover crops grown between the main crops. Without these adjustments, the N content of the soil was too low and hence the simulated wheat yields of 2005 were unrealistically low. This emphasizes the importance of using plausible assumptions to initialize the SOM and N content, and the robust method to initialize is simulation of the pre-experimental period (Bruun & Jensen, 2002).

Based on the above calibration (using SOM and pea height for initiation) and successful validation in the 11-year crop rotation (2005-2016 data), crop yields, total grain N and LAI were simulated for the 2017 experiment. The simulated yields and grain total N values were generally higher than the measured values, especially for the monoculture (Ghaley and Hansen, 2019; Appendix 1). The LAI was not measured in the field experiment, and the simulations of LAI were used to complement the yield and grain N results. The LAI varied between the monocultures and the intercrops in pea and spring barley, and decreased for both crops in the intercrops (Ghaley and Hansen, 2019; Appendix 1). The pea showed higher LAI both in monoculture and in intercrop, which is in line with the much higher total N and grain N values for pea compared with barley in the intercrop.

3.3. Discussion of DAISY model suitability for evaluating mechanisms underpinning beneficial plant associations

The DAISY model showed promising results for barley and field pea, even with initial calibrations using only a few parameters. Adjustments of the share between slow and fast

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SOM pools resulted in better simulation of the total crop N for both N100 and N0 and setting the pool of fast SOM (to 30%) resulted in higher total crop N for simulated N100 compared with the measured data. The initial SOM and N uptake therefore needs further calibration. The calibration of the pea height resulted in significant improvements for the yields.

The overestimation of yields in our simulations could be due to various reasons. The measured yields are from organically managed plots, and so competition from weeds and damage from incidence of pests and diseases in the field experiment may have reduced actual yields compared with simulated yields as DAISY does not take into account the negative effects of weed and incidence of pests and diseases; higher yield estimates are most likely for the pea monoculture due to its greater sensitivity to pests and diseases. Information from the field trial about these factors could not be obtained to verify this explanation. Weeds are a significant problem: Hauggard-Nielsen et al. (2009) emphasize the widespread problem of weeds in pure pea cultures and the benefits of pea-barley intercrops to reduce the weed problem substantially.

Intercrops are complex dynamic systems involving interspecific interactions throughout crop growth, and model simulations should be compared to trends in field data measurements (Manevski et al., 2016). In order to improve the model simulations with respect to the beneficial plant associations in intercrops, the model must be further calibrated for the soil, crop and environmental factors. Based on the results presented above and provided in more detail in Ghaley and Hansen (2019; Appendix 1), some of the required key aspects to consider are:

1. N uptake in the roots, as the barley has a high competitive advantage with early growth and deeper roots. This may be accounted for as we observed lower pea and higher barley yields for N and DM in N100 intercrop.

2. Samplings at key phenological crop stages in field experiments (emergence, tillering, panicle initiation, anthesis, maturity).

3. Measurement of photosynthesis rate and LAI in monocultures and intercrops.

4. The soil N mineralization rate, which might increase with pea crop due to N2-fixation.

5. Calibration of the developmental stage (DS) Rates, as many variables in DAISY are functions of crop development (Manevski et al., 2016). This would require multiple plant samplings during the growth period.

6. The percentage of each species in the mixture might vary over time and according to environmental conditions, and at harvest is usually highly variable (Naudin et al., 2010) and needs to be taken into account for future intercrop scenarios.

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An improved match between observed data and simulations can be achieved when simulating continuous multi-year crop rotations compared to simulation of single years (Kollas et al., 2015). For example, in the future, we plan to grow a barley-pea intercrop trial with different N rates, and the data from this new field trial will improve the robustness of the simulations.

We conclude that the DAISY model is a potentially promising simulation tool for the comparison of pea-spring barley intercrops with their monoculture counterparts. Despite the initial problems to simulate spring barley yields, we showed that parameter changes in terms of the fast and slow fractions of SOM and the pea height (based on development stage) enabled DAISY to simulate acceptable intercrop yields for pea and spring barley, which provides a basis for improving the model simulations by parameterization of soil carbon and nitrogen contents, soil moisture content, LAI and other parameters listed by Ghaley and Hansen (2019; Appendix 1).

4. Comparison and overall evaluation of APSIM and DAISY

The calibration and validation work showed that, for existing crop growth models, like APSIM and DAISY, a large number of field observations that are seldom available are required for proper calibration and validation. Of particular relevance were the within-season observations and initial amounts of soil nitrogen, which, however, were mostly not available in the DIVERSify data sets. Moreover, the limited number of years of data available within DIVERSify so far has complicated the process. For these reasons, data from sources other than the DIVERSify field trials have been successfully sought and used, as detailed in Sections 2.1 and 3.1 above.

By considering these more suitable datasets, both APSIM and DAISY were successfully calibrated and validated for cereal and legume monocultures. Their simulation capabilities were mostly satisfactory for monocultures, in particular under well-fertilized conditions, while the results for intercropping systems are less robust. This pattern suggests that these crop models may be missing some of the aspects driving crop development and yields in intercropping systems. This result confirms one of the premises of the modelling work planned within DIVERSify.

This result emerges consistently from datasets across the rather diverse pedoclimatic conditions considered in this report. Indeed, APSIM was applied to different pedoclimatic conditions, both in terms of validation/calibration (France and the Netherlands) and subsequent comparison with data from the DIVERSify trials (extending from central Sweden to central Italy). Conversely, the work with DAISY has so far focused on Danish conditions. While working across pedoclimatic conditions represents a challenge, with potential negative

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repercussions on the quality of the final results, this kind of work allows the transferability of the calibrated model to be assessed. In this sense, the results obtained with APSIM are promising, as the model was capable of representing observations across different pedoclimatic conditions, at least in monocultures.

The more limited performances of crop growth models in intercrops as compared to monocultures emerges independently of the specific cereal-legume system. APSIM was applied to two sets of crops and the associated intercrop (spring wheat and faba bean; and spring barley and field pea), while only one set of crops (spring barley and field pea) was included in the DAISY work, due to data availability. We note that the pea-barley system – the one used for the work with DAISY – is also the system where APSIM performances were less promising.

The calibration process clearly showed that, among the plant traits, both models point to the importance of correctly estimating LAI, throughout the growing season, i.e., the plant light capturing capability (and the ability of one crop to compete with the other on this matter, in intercrops). Indeed, even relatively small discrepancies between the model simulations and reality may lead to large differences in the final biomass and yield, particularly in the intercropped system. In turn, achieving a robust simulation of LAI requires the correct simulation of the occurrence of the different developmental stages and total plant height (an imprecise estimate of LAI for barley by APSIM is probably the main reason for the limited performance of the model in the barley-field pea system). The importance of including data throughout plant development during the season explains why the calibration procedures of both DAISY and APSIM focused on these aspects, at the cost of employing additional data. The sensitivity of the final results to these aspects is also suggestive of the relevance of these plant traits when considering the potential of these models to simulate intercropping systems.

Environmental conditions played an important role. While no pattern in model performance emerges across climatic conditions (see Fig. 4-5), the role of N availability was key for APSIM performance. The uncertainties inherent in characterizing the N limited conditions forced the focus on well-fertilized crop studies. DAISY appears to be less sensitive to the level of fertilization, at least in its calibrated version (e.g. Fig. 6-8 in Ghaley and Hansen, 2019; Appendix 1). Nevertheless, DAISY also emerges as sensitive to the soil nutrient status, so that it is important to run a few seasons before simulating the focal crop to establish reliable virtual initial conditions (as done for the case of 11 yr crop rotation in Denmark); and to consider well-fertilized plots also in DAISY. Similarly, one key aspect in the validation of DAISY was the initial soil organic matter, which was the focus of an *ad hoc* validation step. As such,

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the calibration procedure and simulation results both point to the importance of a thorough characterization of the soil nutrient status for reliable simulations.

While the results discussed above show some promise, some aspects of the performances of both APSIM and DAISY still require improvements. As pointed out in the description of the calibration and validation work with APSIM and DAISY, several additional steps are planned towards a further improvement of the capabilities of these two models. The goal of this continued work is not only to use these models to describe monocultures and intercrops, but also to identify the key traits and mechanisms driving the interaction of cereals and legumes in the field, by contrasting model results with observations. Some of these steps will be facilitated by the availability of field trial data from DIVERSify, relative to the second season (2018).

5. Evaluation of resource use efficiencies in support of the modelling work

In parallel to the modelling work described above, grain yields as well as N accumulation and use efficiencies were assessed using data collected in the DIVERSify 2017 field trial in Uppsala. This trial focused on twelve different pea-barley and bean-wheat teams, based on different legume and cereal varieties. The N use efficiency was deconstructed into its key elements (N uptake efficiency, yield production per N amount in the crop, yield N content; Weih et al., 2011; 2018), to detect which aspects of N use efficiency were particularly affected by plant-plant interactions.

In terms of grain yield, the legume partners (pea or bean varieties) performed worse in the intercrop systems compared to the monocultures, while the cereal partners (varieties of barley or wheat) strongly benefitted from growing in the intercrop systems (compared to the performance in monoculture) (Ajal, Weih et al, manuscript in prep.). This pattern is partly different from the one seen in the field trials at other DIVERSify field trial locations; for example in the UK site (partner JHI), the legume partners benefitted much more from the intercropping system compared to the cereal partners (not shown). In the Swedish field trial, the differences in yield performance between the plant teams were accomplished more by differences in crop net N accumulation efficiencies, and less by differences in yield production per N amount in the crop (Ajal, Weih et al., manuscript in prep.). In the wheat intercropped with bean, large N amounts were accumulated above-ground by the flowering stage, but a great portion of the N pool at flowering stage was not any longer apparent in the above-ground plant parts at crop maturity; the magnitude of the cereal crop N pool at flowering varied between the wheat varieties grown in the bean-wheat intercropping systems (Ajal, Weih et al., manuscript in prep.). In addition, the pea-barley teams were also assessed in

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terms of species preferences for different N sources and competition for fertilizer N by using ^{15}N methodology; the analysis and evaluation of the corresponding data is currently in progress (Jäck, Weih et al., manuscript in preparation).

These results are relevant for the next steps in the modelling work with APSIM and DAISY. As discussed above, N availability and its accumulation and use by the intercropping system components plays a pivotal role in defining the model outcomes. Knowledge of which aspects of the N economy are most affected by growing these plants in intercrops instead of monoculture may provide further insight into the specific mechanisms of plant-plant interaction involved, and the model parameters that need to be adjusted to capture those mechanisms. These results are also suggestive of which aspects of plant-plant interaction with respect to resource use are of particular relevance and hence should be accounted for when modelling intercropped systems. In the longer run, these results, along with those from the modelling work, will facilitate identifying desirable intercropping systems in an ecological sustainability perspective.

6. Conclusions

APSIM and DAISY showed some promising results for the simulation of spring wheat-faba bean and/or spring barley-field pea systems. The calibration and validation work showed that a large number of field observations is required for a proper calibration and validation of APSIM and DAISY, including some – like within season observations – that are seldom performed in regular field trials. The hitherto limited availability of data within DIVERSify required using data from sources other than DIVERSify in the calibration and validation process.

For monocultures, the APSIM and DAISY simulation capabilities were satisfactory in most cases, while the results were less robust for intercrops. This result indicates that APSIM and DAISY appear to lack capacities to accurately simulate all significant aspects driving crop growth and yields when plants are interacting with each other in intercrops; suggesting that some specific plant-plant interactions not accounted for by these crop models are important for crop performance in intercropping systems. The specific mechanisms underpinning plant-plant interactions are investigated by integrating the modelling work with e.g. the work on resource use efficiencies.

Among the specific crop traits considered here, both APSIM and DAISY require correct estimates of LAI throughout the growing season. Among the environmental conditions, soil nitrogen availability was identified as key for APSIM performance, and a thorough

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characterization of the soil nutrient status was considered important for reliable simulations with both APSIM and DAISY.

To reach the goal of identifying the key traits and mechanisms driving the interaction of cereals and legumes in field conditions across different pedoclimatic regions, additional steps are planned towards a further improvement of the capabilities of APSIM and DAISY; these steps will be facilitated by the additional experimental data (from the 2018 and 2019 growing seasons) that soon will be made available within the DIVERSify consortium.

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Appendix 1

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Evaluation of Daisy model simulations

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Evaluation of Daisy model simulations

Introduction to the Daisy Model

Daisy is a dynamic soil-plant-atmosphere system model for agro-ecosystems. It simulates plant growth and soil processes based on the input of weather data (temperature, precipitation, global radiation and evapotranspiration), soil data (sand, silt and clay content, Carbon (C): nitrogen (N) ratio, bulk density and soil organic matter content), hydraulic parameters, location of ground water and management information (Abrahamsen & Hansen, 2000). Management data required are crop rotation, tillage, use of fertilizer and manure, irrigation, sowing and harvesting. The model simulates water, heat, carbon and nitrogen flows at field scale and provides information on crop productivity and nutrient and water dynamics, as a result of management and weather conditions at a particular site of interest. Daisy can describe processes like soil water transport and flow, evapotranspiration, crop development and growth dynamics (Abrahamsen & Hansen, 2000). It can be linked up to other hydrological models and has been validated in several international comparative validation studies. Daisy is to some degree able to adjust to the available data, either by using simpler models internally when less data is available, or by trying to synthesize the missing data from what is available. Generally, local measurements improve the model description of the studied area. For some input parameters, like precipitation, local measurements are particularly important, because local variability is large and the influence on the simulation results is significant. The original Daisy model has been developed to cope with intercropping situations with more details simulating dry matter in leaf, stem, storage organ and root explicitly (Abrahamsen & Hansen, 2000). For new intercrop combinations to Daisy, like pea-barley used in this study, this setup can be seen as a starting point testing the model on this intercrop system and an offset for further calibration and validation.

1. Model calibration and validation: data sets used and procedure

1.1 Field data

The dataset for calibration was extracted from a field experiment in 2017 on spring barley sole crop (BSC) and pea sole crop (PSC) and pea- spring barley intercrop (IC). The experimental field was located at the Experimental Farm in Taastrup, under the University of Copenhagen, Denmark. Just before sowing, soil was sampled from 0-75 cm depth in four replicates and analyzed by a private company (OK, Laboratorium for Jordbrug). The N mineralization was 18 kg N ha^{-1} with 1.57 mg NO_3-N and 0.1 mg NH_4-N kg^{-1} soil. The year before the trial in 2016, the experimental site was cultivated with malting barley and conventional management practice was followed (field trial record of the experimental farm). Prior to sowing in 2017, Biogrow (NPK 10-3-1), an organic fertilizer was applied at the rate of 12 kg N ha^{-1}, to the field.

Spring barley (cv. Salome) and pea (cv. Mythic) was sown as sole crops and as intercrops in 50:50 ratio in same rows. Both sole crop and intercrop plots were divided into two treatments; 1) 0 kg N/ hectare (N0) and 2) 100 kg N/ha (N100). N100 was applied in two doses of 50 kg N/ha each in the form of urea at 30 and 67 days after emergence (DAE). Sampling of biomass for dry matter (DM) and N content analysis were carried out at 30, 67 and 102 DAE on 31st May, 7th July and 11th August 2017 respectively for the N100 plots and grain yields, DM and N content were recorded for N0 plots at harvest. Grain yields were measured at harvest corresponding to 102 DAE in N100 and N0 plots.

1.2 Input data for the Daisy model simulations

In the soil-plant-water system model Daisy, the soil data used are soil texture and horizons, hydraulic properties, and parameterized denitrification rate. Calibrated soil parameters were taken from previous study carried out at the experimental farm. The weather data is from the local weather station at Taastrup Campus, located within the experimental farm, located approximately 130 m from this experimental field. Spring barley and pea crop input data parameterized for growing conditions and yield targets in Denmark was used. The field was under conventional management for the past four decades. The analyzed soil samples from 2017 field experiment, indicated sufficient phosphorous and potassium content for the target yields under Danish growth environment.

1.3 Calibration procedure

Calibration procedure consisted of the following steps (Figure 1) and is elaborated in the following sections:

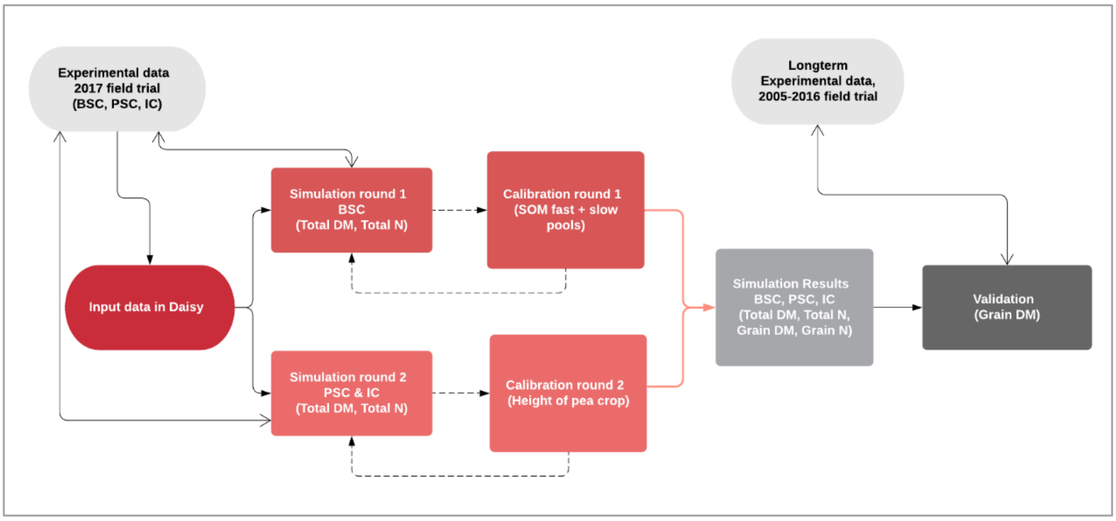

Figure 1. Diagram showing overview of the Daisy model calibration and validation process

1. **Field data processing and synthesis**
   1.1. Experimental data for comparison/validation of simulation
   1.2. Identification of field-specific input data to Daisy
2. **Simulation round 1 with no calibration in barley sole crop**
   2.1. Model simulation of barley sole crop

2.2. **Evaluation**: Comparison of simulation results to measurements below

2.2.1. Total DM

2.2.2. Total N from biomass samples at 30, 67 and at harvest 102 DAE for N100

2.2.3. Total N and DM from biomass samples at harvest for N0.

3. **Calibration round 1**

3.1. Adjustments in the share of fast and slow soil organic matter (SOM) pools + model simulations of barley sole crop

3.2. **Evaluation**: Comparison of simulation results to measurements below (3.1 and 3.2 repeated until best fit)

3.2.1. Total DM and total N at 30, 67 and at harvest 102 DAE for N100

3.2.2. Total N and DM at harvest for N0.

4. **Simulation round 2 on pea and pea - spring barley intercrop**

4.1. Model simulations of pea sole crop and pea- spring barley intercrop

4.2. **Evaluation**: Comparison of simulation results to measurements below

4.2.1.Total N and total DM at 30, 67 and at harvest 102 DAE for N100

4.2.2.Total N and total DM at harvest for N0

5. **Calibration round 2 with pea height adjustments**

5.1. Adjustment of pea height from 100 cm to 50 cm + model simulations of pea sole crop and pea-spring barley intercrop

5.2. **Evaluation:** Comparison of simulation results to measurements below (5.1 and 5.2 repeated until best fit)

5.2.1.Total N and total DM at 30, 67 and at harvest 102 DAE for N100

5.2.2. Total N and total DM at harvest for N0.

6. **Overall evaluation**

7. **Validation with long-term field data**

7.1. See section 2.1.9

1.4 Step 3.1. SOM content of the soil

In the following sections, the justifications for adjusting the parameters in the above simulation and calibration rounds are elaborated:

Daisy simulations are notably influenced by the initial distribution of SOM and changes in management and climate at the site before the onset of the simulated experiment (Bruun & Jensen, 2002). The soil organic matter (SOM) initial conditions are dependent on the specific field conditions and previous management. The initial SOM conditions in this experiment were not known. The N mineralization measured before the beginning of the trial at 18 kg N/ha is sensitive to time of year with respect to weather conditions and management. As no other measurements of SOM or C in the soil was available, this measurement was not used for initial conditions. The experimental field had previously been subdivided into different parcels with various management and hence management information could not be obtained. The initial SOM conditions in Daisy does not correspond to any measurable entities and hence the distribution of SOM cannot be initialized by a simple measurement (Bruun & Jensen, 2002).

The most reliable way of calibrating was therefore to compare a model output (e.g. total crop N) with measured data of the same parameter. The model was initialized with two SOM fractions, a fast and a slow fractions. The percentage of each of the SOM fractions were altered until the simulated total crop N at harvest time matched with the measured data for the N0 and N100 treatments. The same method has been used by Manevski et al., (2016).

1.5 Step 5.1. Height of pea plants

When simulating intercropping, the leaf area index (LAI) was very high for the pea and low for the barley compared to the LAI under Danish growth environments. This resulted in low yields of the barley in intercrops as the pea component out-competed the barley component in the simulation. Hence, the height of the pea was adjusted in the model parameter to simulate height corresponding to development stage (DS) of pea. The pea height was changed to 50 cm at DS1 (flowering) and DS (ripe) from the default settings for sole crop pea at 100 cm. The 50 cm height corresponded well to the heights of the Mythic pea variety used in this experiment with plant heights of 45-55 cm (Sortinfo, 2017).

1.6 Results from the calibration

By calibrating only the rate of mineralization through adjusting the SOM pools, and the height of the pea crop, the outputs from the calibration steps are presented here. In order to improve the model fit and accuracy, further calibration for the soil and crops is needed, which is elaborated in section 2.3.

1.7 Calibration round 1. Calibrations of SOM pool

For BSC N100, the model simulations of total crop N and total DM at 30 and 67 days after emergence fit quite well to the measured values (Figure 2). At harvest, the model overestimates the total crop N of the BSC in N100 treatment. For the unfertilized plot with N0, the simulated total crop N is slightly underestimated. The large standard deviation for the measured data illustrates the uncertainty of simulating only one year of field data. It is complicated to validate the total N status of the soil, which is critical to the simulation accuracy, due to lack of samples at 30 and 67 DAE for the non-fertilized plots. The model fit will be improved with further calibration, and the settings were regarded as useful for calibration, and hence the pea and pea-spring barley intercrop simulations were performed.

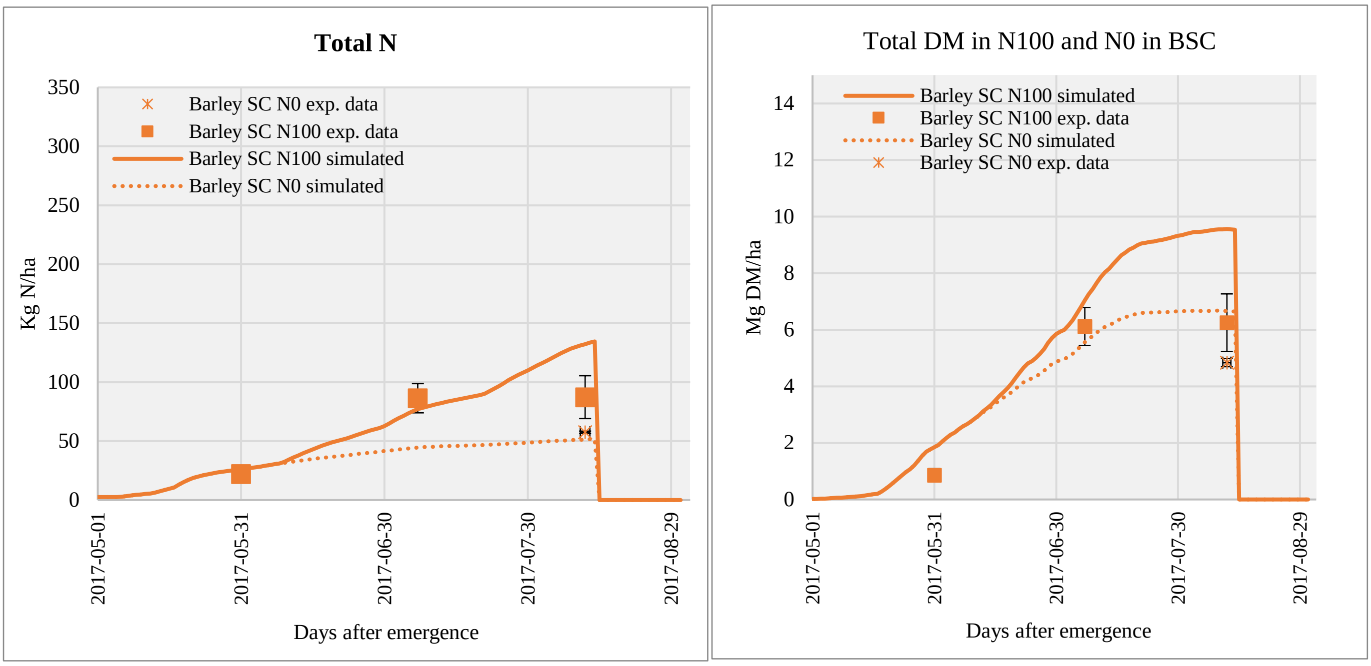

Figure 2. Total N and total DM for spring barley sole crop. Simulation compared with measurements at 30, 67 and 102 DAE (31st May, 7th July and 11th August 2017) for N100 and at 102 DAE for N0.

1.8 Calibration round 2. Pea height adjustments

For PSC at N100, the total crop N content is overestimated in the simulation compared to the measured data at 67 and 102 DAE (Figure 3). The total DM fits quite well with the measured data except at 102 DAE. There is little variation in the PSC simulations between N100 and N0. Also, the total N and total DM are very similar.

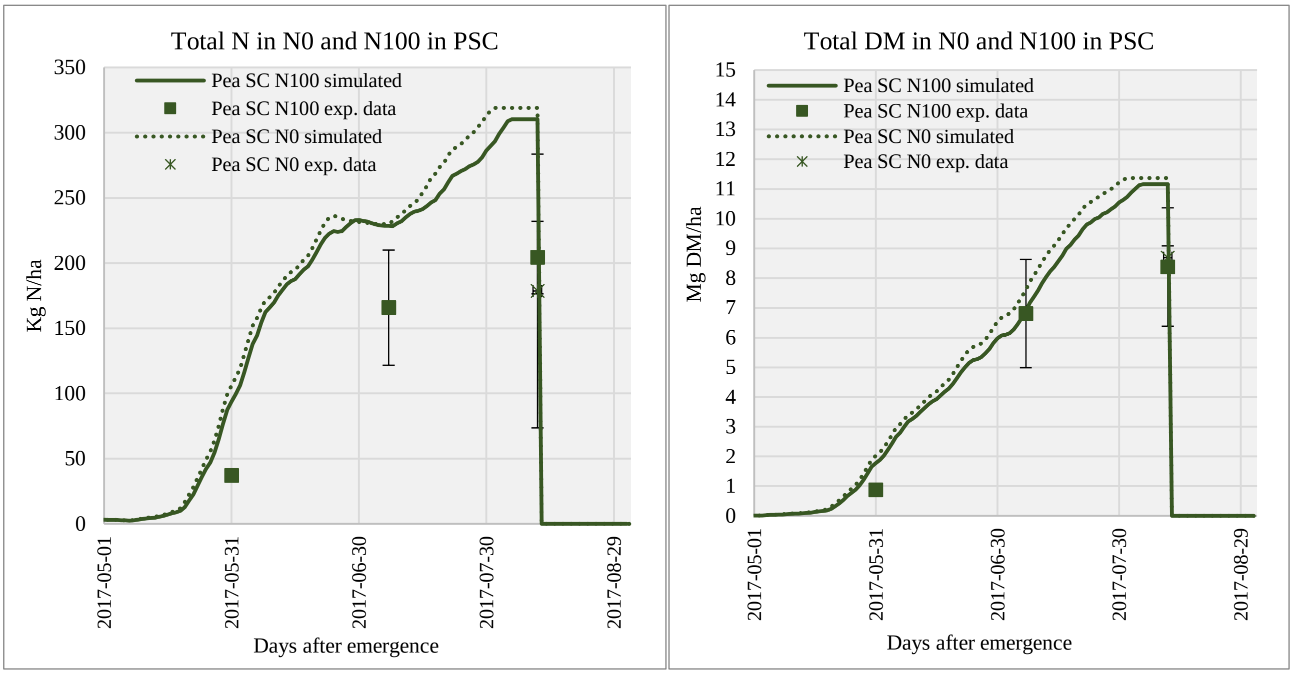

Figure 3. Total N and total DM for pea sole crop. Simulation compared with measurements at 30, 67 and 102 DAE (31st May, 7th July and 11th August 2017) for N100 and at 102 DAE for N0.

The intercrop simulations (Figure 4) for N100, is a good fit for the barley component at the beginning of the growing season, but the measured data shows a larger increase in total N in July and then a decrease at final harvest, whereas the simulation shows a steep increase at the end of the growing season. The total N in crop

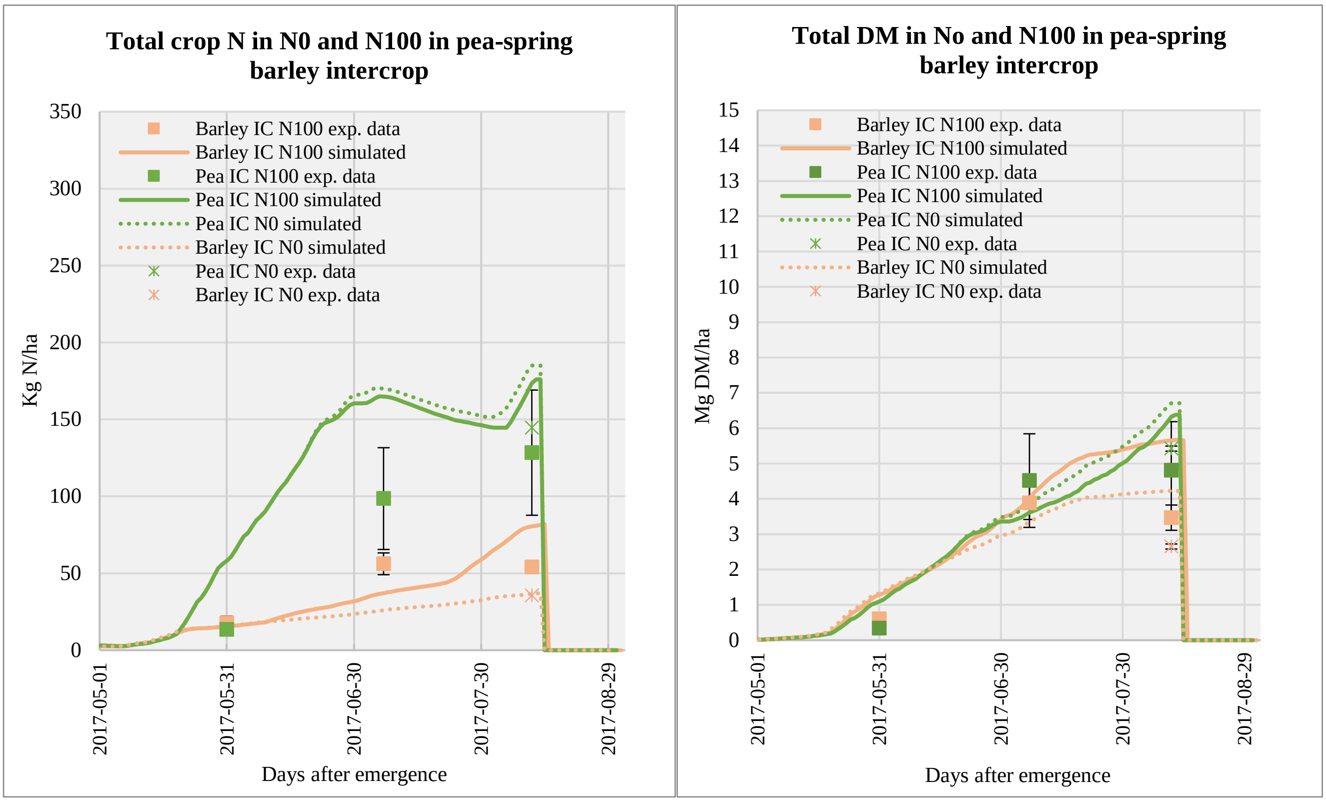

Figure 4. Total N and total DM for intercropping. Simulation compared with measurements at 30, 67 and 102 DAE (31st May, 7th July and 11th August 2017) for N100 and at 102 DAE for N0.

are connected to the difference in N fixation in the pea in N100 and N0 treatments. The PSC fixed 200.8 kg N/ha in N0 and reduced quantity of 143.9 kg N/ha in N100. This shows that N fixation decreased in fertilized plots compared to N0 plots. In the intercrop, barley took up the bulk of the soil nitrogen and the intercropped pea was forced to meet the N requirement through fixation. The increase in N fixation in intercrop has been recorded in other studies (Hauggard-Nielsen et al., (2009). The increased total N in IC compared to SC, is explained by a large uptake of soil N by the barley component forcing the pea to increase N_2-fixation and thereby increase the overall total N in intercrops. Calibration of the soil N and/or calibration of the pea N uptake and N fixation can improve the simulation results. For the measured data, there are large variations in data points at 67 and 102 DAE.

1.9 Step 7. Validation procedure and results

After the calibration, for the validation of the model simulation setup, we simulated an organic 11 year crop rotation (2005-2016) including wheat, barley and pea, though not intercropped. The model simulations was compared to the yields available (Table 1). The management was set to default management in accordance to Danish standard practices on organic farming without fertilizer.

Table 1. Average yields 11 year crop rotation from Højbakkegaard compared to simulated yields without fertilizer (Mg DM/ha). Numbers marked with grey should not be accounted for. The Lucerne crop is not integrated in Daisy and hence pea was used in the simulated crop rotation. Oat was not integrated in Daisy crop library and hence spring barley was used in the crop rotation instead.

Year	Crop	Measured yields (Mg DM/ha)	Simulated yields (Mg DM/ha)
2005	Winter Wheat	3.9	3.3
2006	Spring Wheat	3.0	2.1
2007	Spring Barley	3.4	2.4
2008	Clover	6.5	
2009	Clover	2.8	
2010	Spring Wheat	4.5	3.8
2011	Spring Barley	3.0	3.8
2012	Lucerne (pea)	6.2	6.3
2013	Oat (Spring Barley)	4.1	4.9
2014	Spring wheat	3.4	2.3
2015	Spring Barley	3.4	2.6
2016	Lucerne (pea)	9.1	7.0

The 2005-2016 simulation results show that simulated yields for pea and spring barley are similar to the measured values (Table 1) and with significant correlation between the measured and simulated values (Figure 5). Previous to 2005, two years of clover was simulated to create reliable initial conditions as clover is regularly grown on these fields, as per the crop rotation. For the spring wheat growth in 2006 and 2010, 50 kg N/ha was applied in the simulation to account for N_2-fixation by cover crops grown between the main crops. Without these adjustments, the N content of the soil was too low for and hence the simulated wheat yields of 2005 were unrealistically low. This emphasizes the importance of using plausible assumptions to initialize the SOM and

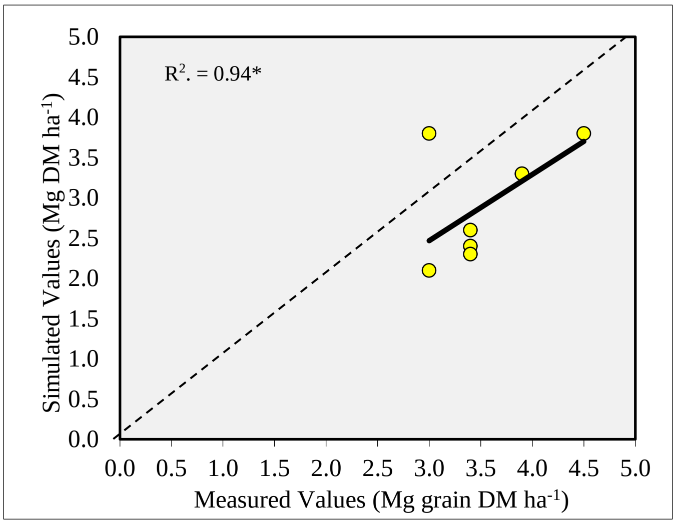

*Figure 5. Correlation between measured yield data from 2005-2016 (long-term yield data and simulated BSC and PSC. Significant at P ≤ 0.05**

N content, and the robust method to initialize is simulation of pre-experimental period (Bruun & Jensen, 2002).

2. Results of model simulations (monocrops and intercrops)

In this section, preliminary results of yields, total grain N and LAI from the model simulations are presented.

2.1 Grain DM yields

In both measured data and simulation results, the intercrop yields are lower than the sole crop yields (Figure 6). For all treatments, the simulated yields are somewhat higher than the measured yields, especially for the sole crop treatments. In this study, the total crop N and total DM did not fit at harvest, so overestimation of yields were expected as well, and the reason for this will be investigated in future calibrations.

The overestimation of yields in simulations can be due to various reasons. The measured yields are from organically managed plots, and so competition from weed and damage from incidence of pests and diseases in the field experiment may have reduced the yields. Daisy does not take into account the negative effects of weed and incidence of pests and diseases, and hence a higher yield estimates are possible, most likely for the pea sole crop due to its sensitivity to pests and diseases. Information from the field trial about these factors could not be obtained. Weed is a significant problem and Hauggard-Nielsen et al., (2009) emphasize the widespread problem of weed in PSC and benefits of pea-barley intercrop to reduce the weed problem substantially.

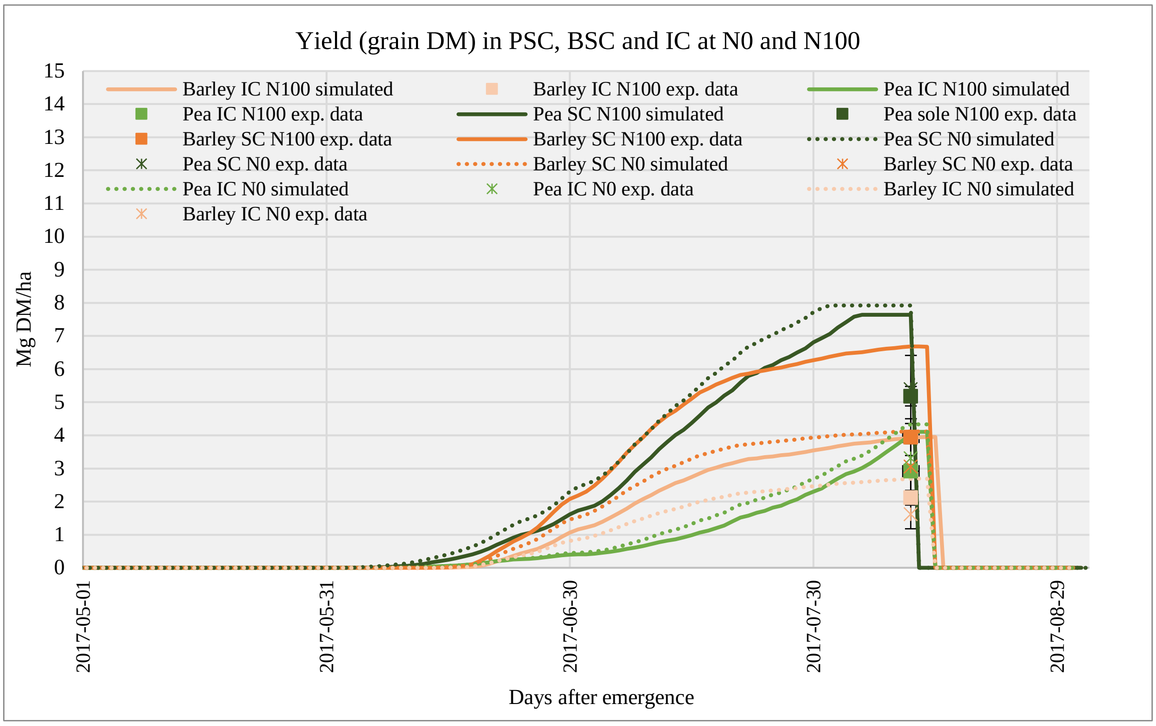

Figure 6. Yield. Comparison of sole crop and intercrop treatments with 100 kg N/ha and 0 kg N/ha at 102 DAE, 11th of August 2017, and illustration of the simulations development during the growing season.

2.2 Total grain N content

The grain total N shows overestimation in the simulations in similarity to total crop N (Figure 7), especially for the PSC as expected from the calibration results. It needs further investigation of the pea calibration in

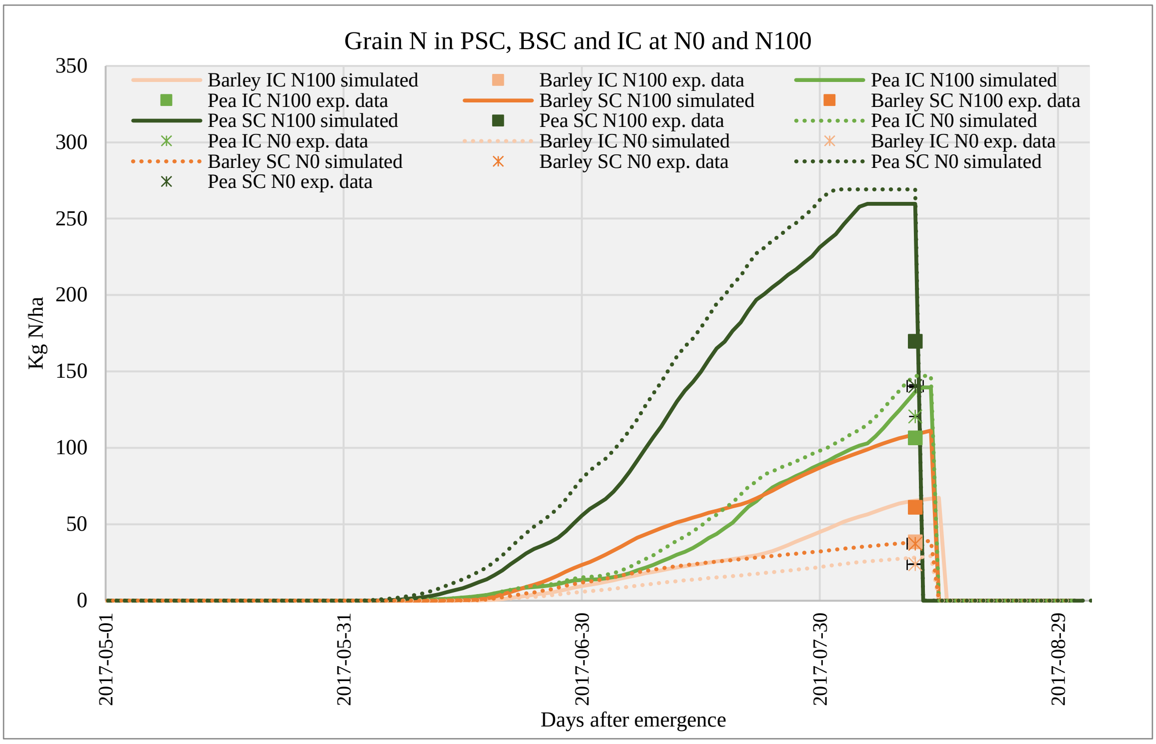

Figure 7. Total N. Comparison of sole crop and intercrop treatments with 100 kg N/ha and 0 kg N/ha at 102 DAE, 11th of August 2017 and illustration of the simulations development during the growing season.

daisy to identify the reasons for the overestimations. For intercropping, pea is close to the measured value with little difference between the N0 and N100 results for both measured and simulated results. This can be due to ability of pea to supplement N needs from the soil N with N_2-fixation when barley dominates the soil N uptake. The simulated grain N and grain yield for barley intercrop at N0 results were better than at N100. In similarity, the intercropped barley simulation results were better compared to the BSC simulation results.

2.3 LAI

These results are only from the simulations as no measurements of LAI was performed in the field experiment. It is used to compare and support the DM and N results. There are differences in the LAI between the sole

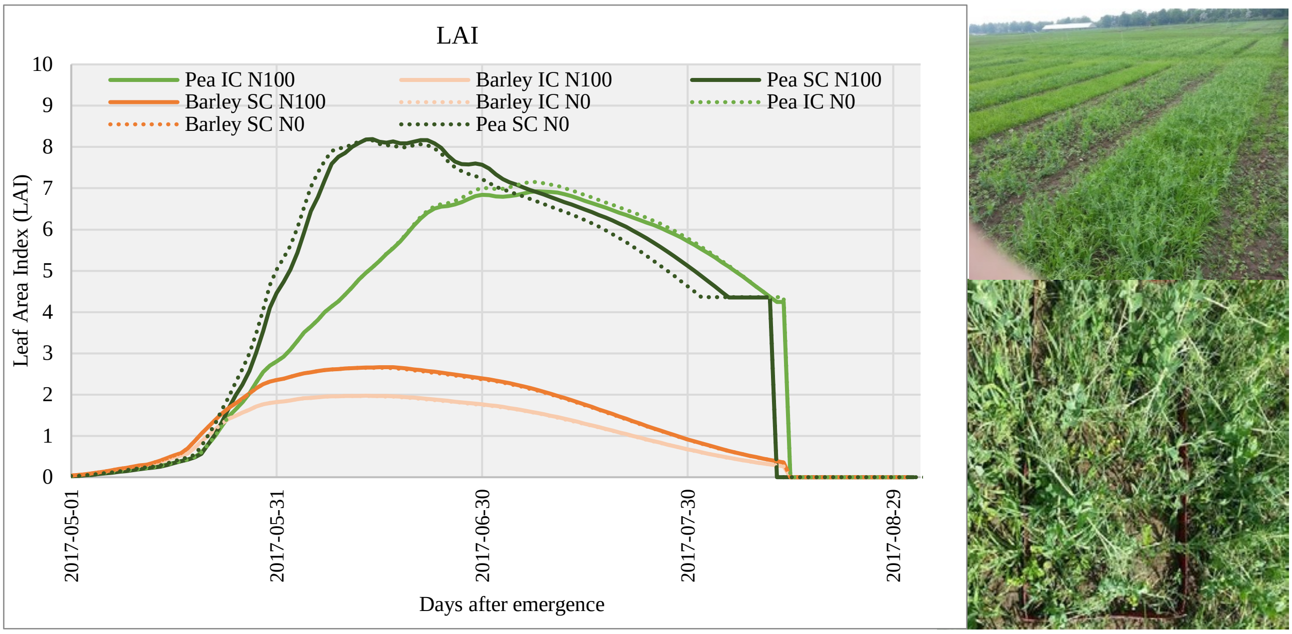

Figure 8. LAI from simulations (left), photos of the intercropped field in 2017 (right). Due to indifference in LAI for spring barley intercropped both at N100 and N0 these lines cannot be distinguished from the sole crop lines.

crops and the intercrops in pea and spring barley (Figure 8). LAI decreases for both crops in the intercrops, which is justified due to competition for space. The pea has higher LAI both in sole crop and in intercrop. This is in line with the much higher total N and grain N values for pea compared to barley in the intercrop. Comparing to pictures from the field trial shows that a high LAI for pea compared to barley is reasonable, as the pea covered a larger share of the area in the plots at the latter part of the growing season. For barley, there is no change from N0 to N100 in the LAI. This needs further investigations as the other studies have shown differences between treatments. The low LAI of barley and very high LAI of pea in intercrop corresponds with the higher DM for pea than barley in intercrops and the magnitude of the LAI difference needs further investigations.

3. Discussion on evaluating mechanisms underpinning beneficial plant associations

3.1 Overall model suitability

The Daisy model have shown promising results with these preliminary results presented with initial calibrations of only a few parameters. In order to improve the simulation fit, the requirement of experimental results are discussed below with reference to other studies on intercrops.

3.1.1 Comparison of SC and IC

The results from this study shows more total DM, total N, grain DM and grain N in pea SC than pea IC. Hauggard-Nielsen et al., (2001) similarly identified a decline in pea yields when intercropped with barley and Hauggard-Nielsen et al., (2009) identified reduced soil N uptake by pea when intercropped with barley. A large uptake of soil N by the barley results in forcing the pea to increase N_2-fixation and thereby increase the overall total N in intercrops.

Cereals can reduce the growth of pea in intercropping if the soil N availability is adequate. The cereals can utilize the abundant soil N fast and therefore compete better for the light in the beginning of the growing season. This high N uptake by barley component can reduce the pea growth (Corre-Hellou et al., 2011). The model identified the same trends as the measured data in PSC had higher values compared to IC.

3.1.2 Comparison of N0 and N100 yields

The total DM, grain DM, total N and grain N in IC was higher in the non-fertilized plots for pea intercropping compared to the fertilized plots. This corresponds to other findings. Ghaley et al., (2005) found maximum productivity increase without fertilizer for intercropped pea and wheat when tested at 0, 4 and 8 g N m^{-2}. The intercropping increased the total DM, total N, grain DM and grain N, N soil accumulation and N derived from N_2 fixation (Ghaley et al., 2005).

The model does not show any significant differences in pea productivity in N0 and N100. Pea crops can be quite independent of N fertilizer due to the N_2 fixation and Naudin et al., (2010) found no effects of N fertilizer on the amount of N_2 fixed by intercropped peas compared to the unfertilized plots. It must be further investigated how to incorporate better response of the pea to fertilizer and intercropping.

3.1.3 LAI

Corre-Hellou et al., (2011) have looked into studies of barley and pea intercrop effects on weed and interactions on crop productivity. The spring barley in this study had similar LAI of 2.6 in sole crop compared to 2.7 in sole crop in Corre-Hellou et al., (2011) study. In this study, the pea show higher LAI of 8.13 for sole crop compared to 4.7 in another study (Corre-Hellou et al., (2011). In the intercrop, the pea in this study have high LAI of 6.8 resulting in higher LAI values for total IC. LAI have been linked to soil N availability and more N availability is correlated to the higher LAI (Corre-Hellou et al., 2011). From the Daisy simulations, the total N content and the total DM of the pea SC is not affected by the fertilizer rate unlike the measured data. The simulation results for pea SC is high (294.1 kg N/ha and 6.3 Mg DM/ha) compared to the measured values (204.3±27.8 and 5.2± Mg DM/ha for N100 and 225.3±104.9and 5.4±1.0 Mg DM/ha for N0). The high pea yield due to high LAI values show that the pea growth might be overestimated in the Daisy model simulations. The measured data for the pea SC N0 and pea IC N100 does vary to a small degree, which show that the simulations are within the range of the measured data. Pea is usually quite unaffected by the soil N availability because of their complementary use of atmospheric N and inorganic N (Voisin et al., 2002).

3.1.4 Overestimations

At harvest, the simulations of total DM, total N, yield and grain N are overestimated, except for the non-fertilized barley grain N which fit well with the field measurements. Kollas et al., (2015) have experienced similar systematic overestimations for barley yields for both multi-year modelling and single year modelling, when testing 15 different crop models including Daisy with only a few calibration factors included.

3.2 Late N application effects on crop yields

The abovementioned overestimation is, however, is not necessarily solely a sign of bad fit for the model. The 2 x 50 kg N/ha was applied late in the season late compared to normal practice and hence the uptake and use of the applied N of the spring barley might have been smaller compared to the outcome of an early application. In 2017 it rained quite a lot in June and July and the applied N might have been partly lost through leaching if not utilized by the plants at the application timing. It is assumed that delayed N application after sowing could change the inter-specific dynamics in competitive ability of the cereal and the effects on N_2 fixation from N application at different stages. Naudin et al., (2010) tested the timing of N fertilization in wheat-pea intercropping on the percentage of each species and N_2-fixation and concluded that N fertilization independent of timing always increase the wheat growth and decrease pea growth.

3.3 Evaluation of calibrations

Adjustments of the share between slow and fast SOM pools did result in better simulation in the total crop N for both N100 and N0 and the setting of the pool of fast SOM (30 %) did result in higher total crop N for simulated N100 compared to the measured data. The initial SOM and N uptake therefore needs further calibration. The calibration of the pea height resulted in significant improvements for the yields, increasing the simulated IC barley yields from around 0.05 Mg DM/ha (data not shown) to more realistic values, provided in figure 6 and figure 7.

3.4 Calibration data

Intercrops are complex dynamic systems involving interspecific interactions throughout crop growth (Naudin et al., 2010). In order to improve the model simulations with respect to the beneficial plant associations in the intercrop trial, the crops must be further calibrated for soil, crop and environmental factors. Some of the key calibrations include:

1. N uptake in the roots, as the barley have a high competitive advantage with early growth and deeper roots. This may be accounted for as we find lower pea and higher barley yields for N and DM in N100 intercrop.
2. Samplings at key phenological crop stages in field experiments (emergence, tillering, panicle initiation, anthesis, maturity)
3. Measurement of photosynthesis rate and LAI in sole and intercrops
4. The soil N mineralization rate, which might increase with pea crop due to N_2-fixation
5. Calibration of the DS Rates, as many variables in Daisy are functions of crop development (Manevski et al., 2016). This would require multiple plant sampling during the growth period
6. The percentage of each species in the mixture might vary over time and according to environmental conditions, and at harvest is usually highly variable (Naudin et al., 2010) and needs to be taken into account for future intercrop scenarios.

3.5 Long-term experimental data for validation

Because of the high complexity of the simulated soil and crop processes, the model simulations should be compared to the trend in field data measurements (Manevski et al., 2016). Ideally, a warm up simulation period before the actual simulation period with inputs on previous known management, fertilizer and crop residues inputs, should be incorporated in the model to approximately estimate the annual net mineralization rate. Performing model validation on several independent datasets increases robustness and improve the simulation outputs (Manevski et al., 2016). In the coming growing season of 2019, a barley-pea intercrop trial with different N rates is planned on the same experimental location. The data from field trial in 2019 will improve the robustness of the simulations. Higher quality of simulations can be achieved with continuous multi-year crop rotations compared to simulation of single years and singe crops as per the findings from validation of fifteen crop growth simulation models including Daisy (Kollas et al., 2015). Statistical analysis (and sensitivity analysis) of the results from the simulations are needed in order to improve the robustness of the model outputs. Based on this report and experience with the DAISY modelling exercise, a table (Table 2) of desirable parameters is identified for field measurement in order to calibrate and validate the model for intercrops.

Table 2. Overview of parameters required for the daisy model to simulate sole and intercrops

Data	Data variable 1	Data variable 2	Data variable 3	Frequency
Weather	Global radiation WM2	Air Temp (°C)	Precipitation (mm)	Hourly
Soil samplings (sole and intercrops)	Total N	Total carbon	SOM	Before sowing and after harvest
Seed rate	Plant number /m2	Plants/ha		
Emergence count at plant emergence	Counting the no. of plants of each species at emergence			
Plant sampling in different N treatments (0,50,100, 150 kg N/ha) at different growth stages (BBCH Scale)	6 biomass samplings in total and every 15 DAE	6 plant height measurements every 15 AE		Every 15 DAE (DM, Total N, Grain DM, Grain N)
Soil sampling and soil moisture	3 soil depth sampling (15, 30, 50 cm) at every soil moisture measurement	6 soil moisture measurements in total and every 15 DAE (same timing as plant samplings)		
LAI measurement	6 measurements in total and every 15 DAE coinciding with biomass samplings	Alternatively, drones can be used to measure LAI		
Photosynthesis measurement	6 measurements in total and every 15 DAE coinciding with biomass samplings			

3.6 Conclusion

The DAISY modelling exercise has demonstrated that the pea-spring barley intercrop can be simulated for comparison with sole pea and spring barley. At the start of the modelling exercise, simulated spríng barley yields were extremely low due to overshadowing by pea plants. With parameter changes made to the fast and slow fractions of SOM and reducing the pea height based on development stage, DAISY was able to simulate acceptable intercrop yields of pea and spring barley and this provides a rational and well-justified basis for improving the model simulations by parameterization of soil carbon and nitrogen content, soil moisture content, LAI and other parameters listed in Table 2. In 2019, an intercrop trial is planned to record the required soil, plant and management variables during the growth period of the crops in order to fulfill the parameter requirements to improve the DAISY simulations in line with the measured field data.

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