

Response to reviewer's comments

- 1) Observed yields at global and country scale show increasing trends, whereas the model simulates more constant yields with variability. The authors seem aware of this and have de-trended the country data in the figure, but they do not discuss the underlying cause of the observed increase (and why this increase is not expected to arise in the model).

Text added – “Country yields observations were de-trended for comparison with model output. This is because the increasing trend in yields observations over the last fifty years is due to improvements in agricultural technology and management and increasing atmospheric carbon dioxide. This trend is not reproduced by the model as these processes were not represented in our set-up.”

- 2) The national statistics depicted in Fig. 6 give a good insight in the model's abilities, but point at some major weaknesses as well. The authors acknowledge the difference in variability between the model and the observations in their discussion, but other than that there is little discussion about the strong deviations that are seen for many countries. To state that the model "does a reasonable job of reproducing the inter-annual variability at the ... country scale" (Maize) seems flawed (yes, the two may show a correlation, but the amplitude of the variations differs greatly), and I would expect a comment on the strong deviations between observed and simulated yields for many Southeast Asian countries (India, Bangladesh, Indonesia, Thailand) as well.

Text added -

“This may also explain why there are strong deviations between the magnitude of observed and modelled yield in tropical countries where climatic conditions for growth are good in the absence of the limitations described above.”

“For some countries simulations of yield capture the magnitude and variability of observations. In other countries the model reproduces the variability in yield but over-predicts the magnitude. There are also countries where the model performs poorly in simulating both variability and magnitude. This variety of results is due in part to the use of generic parametrizations for global model runs which is a limitation of this type of Earth System Model set-up. By using parameters that do not vary spatially we can not fully represent the range of crop varieties that are found globally.”

Manuscript prepared for Geosci. Model Dev. Discuss.
with version 2014/05/30 6.91 Copernicus papers of the L^AT_EX class copernicus.cls.
Date: 19 March 2015

JULES-crop: a parametrisation of crops in the Joint UK Land Environment Simulator

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Abstract

Studies of climate change impacts on the terrestrial biosphere have been completed without recognition of the integrated nature of the biosphere. Improved assessment of the impacts of climate change on food and water security requires the development and use of models not only representing each component but also their interactions. To meet this requirement the Joint UK Land Environment Simulator (JULES) land surface model has been modified to include a generic parametrisation of annual crops. The new model, JULES-crop, is described and evaluation at global and site levels for the four globally important crops; wheat, soybean, maize and rice. JULES-crop demonstrates skill in simulating the inter-annual variations of yield for maize and soybean at the global and country level, and for wheat for major spring wheat producing countries. The impact of the new parametrisation, compared to the standard configuration, on the simulation of surface heat fluxes is largely an alteration of the partitioning between latent and sensible heat fluxes during the later part of the growing season. Further evaluation at the site level shows the model captures the seasonality of leaf area index, gross primary production and canopy height better than in standard JULES. However, this does not lead to an improvement in the simulation of sensible and latent heat fluxes. The performance of JULES-crop from both an earth system and crop yield model perspective is encouraging. However, more effort is needed to develop the parameterisation of the model for specific applications. Key future model developments identified include the introduction of processes such as irrigation and nitrogen limitation which will enable better representation of the spatial variability in yield.

1 Introduction

Understanding how climate variability and change will impact upon crop production systems is a research challenge of utmost importance to society. To date, studies of climate change impacts on the terrestrial biosphere have been completed without recognition of the integrated nature of the biosphere. Crop simulation models are widely utilised as they incorporate many known effects of how changes in atmospheric conditions can impact upon crop growth, develop-

ment and yield. However, they do not simulate the wider interactions of crops and the environment. For example, climate change will impact upon water resources which will in turn impact upon the water available for irrigation of crops. ? used the Hadley Centre Earth System Model (HadGEM2-ES) to evaluate climate impacts on the terrestrial biosphere under a range of emission scenarios. By doing so they were able to assess several elements of the terrestrial system in a way that was fully integrated and consistent with the climate projections. However, they were only able to include natural systems as crops are not yet included in the model. Including a representation of crops within land surface models will facilitate a more comprehensive, integrated and internally-consistent simulation of the impacts of climate change and variability on the full land system, accounting for interactions between different components and processes. This will ultimately enable improved projections of the impacts of climate change on food and water security, including interactions between the two. There is increasing evidence that the cultivation of crops affects weather and climate on local scales. Crop-lands now occupy 12 % of the Earth's ice-free land surface and in several regions of the world are the dominant vegetation type on the land surface (e.g. mid-West USA, Indo-Gangetic Plain). This extensification of agriculture has altered the biophysical characteristics of the land surface potentially altering regional climate. Therefore, there is reasoning to consider crops and climate as a truly coupled system and hence motivation to develop models which can fully represent the coupled feedbacks between them.

Efforts to simulate the environmental impacts on crop production is commonly thought to have begun in the 1960s at Wageningen (?). Since then crop modelling has grown and there are now many models available in the research and agronomic domains. Such models have been deployed both as decision support tools, and to research the impacts of climate change on future crop production. Recent advances in crop modelling include the application of crop models, traditionally developed at the field level, to cover the globe on a gridded basis (??), and inter-comparison of many crop models in simulating the same crop and the same set of conditions (?).

The investigation of how crop-lands affect weather and climate is much less mature. Initial expansion of crop-land area came at the expense of forests and the impact of this deforestation has received considerable research attention. However, crop-lands have also replaced more

similar native grasslands. For example, ? showed that the near-surface climate over the now intensively cultivated winter wheat belt in Oklahoma, USA, is significantly different to that over adjacent grasslands. ? identify the differences in phenology between managed crop-lands and natural grasslands as the determinant of the differences.

60 The increase in understanding of how crop-lands might differentially impact the climate compared to natural vegetation has led to a recent surge in model development whereby land surface or global vegetation models have been extended to include explicit parametrisations of crops, in place of the use of grasslands as a surrogate (see review of ?). Some developments have been motivated by improving the carbon and water budget of land surface modelling (?), others
65 to include crop-lands in global or regional climate models to better represent their impact on the atmosphere (???), while others have been motivated to consistently simulate both yield and environmental impacts (?).

The aim of this model development was to develop a combined land surface and crop model capable of simulating both the impacts of climate variability on crop productivity, as well as the
70 impact of crop-lands on the climate. To achieve this we have added a crop-specific parametrisation to the Joint UK Land Environment Land Surface land surface model (JULES). JULES is the land surface scheme of the UK Met Office Unified Model and the next generation UK Earth System Model (UKESM) and therefore, can be in time coupled to a state of the art climate model. A full description of JULES can be found in ? and ?. JULES does not currently
75 include an explicit parametrisation of crops, instead over cropped regions the C₃ or C₄ grass plant functional type are used. Previous work has included crops in the model. ? included a crop parametrisation in MOSES (i.e. in the fully coupled land-surface – climate model) based on the groundnut version of the crop model GLAM. More recently, ? extended JULES to include a parametrisation of wheat based on the crop model SUCROS. Neither ? nor ? developed
80 a generic representation of crops suitable for the examination of different crops throughout the globe something that is important from an Earth System Modelling perspective. Therefore, the objective of this study was to develop a generic parametrisation of crops applicable to many crop types and at the global scale. However, the model has been designed to be flexible mean-

ing users can re-parametrize the model depending on requirements (e.g. to represent different
85 crop cultivars).

The following Section describes the model development, Sects. ?? and ?? present evaluation
of the new model when applied at global and site levels, respectively, followed by a Discussion
(Sect. ??).

2 Model description

90 The essence of JULES-crop is illustrated in Fig. ?. The additional model equations required to
simulate crops essentially partition the carbon uptake of vegetation already simulated by JULES
in to several crop organs and the size of the crop, important for land surface-atmosphere feed-
backs, is derived from the organ biomass using allometric equations. The pattern of partitioning
of assimilated carbon to the crop organs is affected by the crop development rate which itself is
95 influenced by temperature. In addition to the new equations describing crop growth and devel-
opment, changes to the model structure were also required to accommodate the additional plant
functional types. New equations describing crop growth and development were added to the
model. Each crop is considered as an additional plant functional type and a distinction is made
between natural and crop plant functional types within the model, with the crop plant functional
100 types requiring extra parameters to be specified. The detailed description of the crop paramet-
risation is split in to three parts. Firstly, the equations that determine the start and duration of the
crop *growing season* are described. Secondly, the equations determining the rate of crop *growth*
are described. Lastly, the changes to model structure are outlined. A full listing of new model
parameters and variables can be found in Tables ?? and ??, respectively.

2.1 Growing season and development

105 The crop growing season begins when the crop is sown. This date can either be prescribed (i.e.
if it is known) or calculated dynamically based on environmental criteria. In the latter case,
sowing only occurs when the soil is wet enough ($\theta_2 > \theta_{c,2}$, where θ_2 is the soil moisture content

in the second layer and $\theta_{c,2}$ is the critical soil moisture content in the second layer), it is warm enough ($T_{\text{soil},3} > T_b + 2\text{K}$, where $T_{\text{soil},3}$ is the temperature in the third soil layer and T_b is the base temperature), and days are not rapidly shortening ($dP/dt > -0.02$ hours per day, where P is the day length). We wish to make users aware of this sowing option however, we feel it needs further optimizing and so results using the dynamic sowing date will not be included here. The use of sub-surface soil moisture and temperature variables prevents sowing occurring too early in response to short term fluctuations in weather. The rate of day length criteria ensures that crops are not sown too late in the year when conditions for growth are deteriorating.

Once sown, the crop develops through three stages: sowing to emergence, emergence to flowering, and flowering to maturity. Harvest is assumed to occur at crop maturity. The rate of crop development is related to thermal time. Given the 1.5 m tile temperature (T), an effective temperature (T_{eff}) is calculated based upon the crop-specific cardinal temperatures (T_b, T_o, T_m - see Table ?? for description).

$$T_{\text{eff}} = \begin{cases} 0 & \text{for } T < T_b \\ T - T_b & \text{for } T_b \leq T \leq T_o \\ (T_o - T_b) \left(1 - \frac{T - T_o}{T_m - T_o}\right) & \text{for } T_o < T < T_m \\ 0 & \text{for } T \geq T_m \end{cases} \quad (1)$$

T_{eff} is greatest, and hence development fastest, at $T = T_o$. As temperature falls below, or rises above T_o the rate of development linearly decreases until no development occurs when either $T \leq T_b$ or $T \geq T_m$. For the sowing to emergence phase, T_{eff} is not affected by T_m or T_o (i.e. $T_{\text{eff}} = T - T_b$). This equation is a “standard” way of calculating effective temperature (?). An important difference to other available models, is that JULES-crop simulates a decline of T_{eff} above the maximum temperature, whereas others keep T_{eff} at the maximum value no matter how high temperatures get.

For some crops, progress towards flowering is slowed if the day length (P) is less than (greater than) a crop-specific critical photoperiod (P_{crit}) for long-day (short-day) crop types. The degree of sensitivity to photoperiod is represented by the parameter P_{sens} which is positive

135 for short-day plants and negative for long-day plants. This conceptual approach was motivated by ?. Therefore, to slow development T_{eff} is multiplied by the relative photoperiod effect (RPE), which is defined as follows:

$$\text{RPE} = 1 - (P - P_{\text{crit}})P_{\text{sens}} \quad (2)$$

140 The status of crop development is represented by the Development Index (DVI) which takes the value of -1 upon sowing, increasing to 0 on emergence, 1 at the end of vegetative stage and 2 at crop maturity. The rate of increase of DVI is calculated as follows where TT_{emr} is the thermal time between sowing and emergence, TT_{veg} is the thermal time between emergence and flowering and TT_{rep} is the thermal time between flowering and harvest:

$$\frac{d\text{DVI}}{dt} = \begin{cases} \frac{T_{\text{eff}}}{\text{TT}_{\text{emr}}} & \text{for } -1 \leq \text{DVI} < 0 \\ \left(\frac{T_{\text{eff}}}{\text{TT}_{\text{veg}}} \right) \text{RPE} & \text{for } 0 \leq \text{DVI} < 1 \\ \frac{T_{\text{eff}}}{\text{TT}_{\text{rep}}} & \text{for } 1 \leq \text{DVI} < 2 \end{cases} \quad (3)$$

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The growing season ends when $\text{DVI} = 2$ at which time the prognostic variables related to crop growth ($L, h, C_{\text{root}}, C_{\text{harv}}, C_{\text{resv}}$) are reset to minimal values close to zero. To prevent growing seasons continuing indefinitely when conditions are no longer suitable the crop is also harvested if the soil temperature in the second soil layer falls below T_b at any time after $\text{DVI} = 1$ or if $\text{LAI} > 15$. Vernalisation, a cold temperature requirement for development in some crops, is not included in this model version.

150

2.2 Growth

To simulate crop growth, Net Primary Productivity (Π) is accumulated over a day and then partitioned between five carbon pools: root (C_{root}), structural stem (C_{stem}), stem reserves (C_{resv}), leaves (C_{leaf}), and harvested organs (C_{harv}). The original formulation for Π in JULES includes

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assumptions about the sizes of the leaf, stem and root carbon pools in order to estimate respiration losses. Stem carbon is a function of leaf area index (Eq. 42 of ?) and root carbon is set to equal leaf carbon. Because these carbon pools are now explicitly simulated, Π is recalculated for the crop types with the following equation based on an algebraic reduction of the set of equations used in JULES:

$$\Pi = 0.012(1 - r_g) \left(A_c - R_{dc} \left(\frac{C_{\text{root}} + C_{\text{stem}}}{C_{\text{leaf}}} \right) \right) \quad (4)$$

where r_g is the fraction of Gross Primary Productivity less maintenance respiration that is assigned to growth respiration, A_c is the net canopy photosynthesis, and R_{dc} is the rate of non-moisture stressed canopy dark respiration. C_{leaf} , C_{stem} and C_{root} are the carbon content of leaf, stem and root, respectively.

The carbon in Π is accumulated over a day and then divided into five crop components according to “partition coefficients”, one for each of the four root, stem, leaf and harvest pools defined above and a reserve pool. These components are added to the (state variable) pools of carbon describing the crop.

$$\begin{aligned} \frac{dC_{\text{root}}}{dt} &= p_{\text{root}}\Pi \\ \frac{dC_{\text{leaf}}}{dt} &= p_{\text{leaf}}\Pi \\ \frac{dC_{\text{stem}}}{dt} &= p_{\text{stem}}\Pi(1 - \tau) \\ \frac{dC_{\text{harv}}}{dt} &= p_{\text{harv}}\Pi \\ \frac{dC_{\text{resv}}}{dt} &= p_{\text{stem}}\Pi\tau \end{aligned} \quad (5)$$

where τ is the fraction of stem carbon that is partitioned in to the reserve pool. $p_{\text{root}} + p_{\text{leaf}} + p_{\text{stem}} + p_{\text{harv}} = 1.0$.

Partition coefficients for a given crop are typically pre-defined in process-based crop models according to either the length of time since emergence, or to crop development stage (DVI, i.e. a function of thermal time since emergence). They are represented by fixed values for a given period of time (or thermal time) since emergence, and these values are listed in a look-up table and referenced for each iteration of the model (e.g. WOFOST, ?).

Here we define the partition coefficients as a function of thermal time using 6 parameters to describe continuously varying partition coefficients over the duration of the crop cycle. We use a multinomial logistic to define this function:

$$\begin{aligned}
 p_{\text{root}} &= \frac{e^{\alpha_{\text{root}} + (\beta_{\text{root}} \text{DVI})}}{e^{\alpha_{\text{root}} + (\beta_{\text{root}} \text{DVI})} + e^{\alpha_{\text{stem}} + (\beta_{\text{stem}} \text{DVI})} + e^{\alpha_{\text{leaf}} + (\beta_{\text{leaf}} \text{DVI})} + 1} \\
 p_{\text{stem}} &= \frac{e^{\alpha_{\text{stem}} + (\beta_{\text{stem}} \text{DVI})}}{e^{\alpha_{\text{root}} + (\beta_{\text{root}} \text{DVI})} + e^{\alpha_{\text{stem}} + (\beta_{\text{stem}} \text{DVI})} + e^{\alpha_{\text{leaf}} + (\beta_{\text{leaf}} \text{DVI})} + 1} \\
 p_{\text{leaf}} &= \frac{e^{\alpha_{\text{leaf}} + (\beta_{\text{leaf}} \text{DVI})}}{e^{\alpha_{\text{root}} + (\beta_{\text{root}} \text{DVI})} + e^{\alpha_{\text{stem}} + (\beta_{\text{stem}} \text{DVI})} + e^{\alpha_{\text{leaf}} + (\beta_{\text{leaf}} \text{DVI})} + 1} \\
 p_{\text{harv}} &= \frac{1}{e^{\alpha_{\text{root}} + (\beta_{\text{root}} \text{DVI})} + e^{\alpha_{\text{stem}} + (\beta_{\text{stem}} \text{DVI})} + e^{\alpha_{\text{leaf}} + (\beta_{\text{leaf}} \text{DVI})} + 1}
 \end{aligned} \tag{6}$$

where α and β are empirically derived parameters describing the shape of the thermal time varying partition coefficient for leaves, roots and stems, and DVI is the development index. Thus for only six parameters (which is also the absolute minimum number of parameters needed to define partition coefficients for four carbon pools) we can define a much wider range of shapes of thermal time varying partition coefficients. What's more, these six parameters can be more feasibly calibrated than a larger number of 'look-up' partition coefficients. This parametrisation is illustrated in Fig. ?? overlaid with example observed partitioning fractions from ?.

Following the formulation of ?, once carbon is no longer partitioned to stems, carbon from the stem reserve pool is mobilised to the harvest pool at a rate of 10 % a day:

$$\left. \begin{aligned}
 C_{\text{harv}} &= C_{\text{harv}} + (0.1 C_{\text{resv}}) \\
 C_{\text{resv}} &= 0.9 C_{\text{resv}}
 \end{aligned} \right\} \text{ for } p_{\text{stem}} < 0.01. \tag{7}$$

Leaf senescence is treated simplistically by mobilising carbon from the leaf to the harvest pool at a rate of $0.05d^{-1}$ once DVI has reached 1.5 This equation was inspired by Eq7, but based the period for which senescence starts on a specific DVI value (1.5) rather than waiting for partitioning to leaves to cease since for some crop types this does not happen. :

$$\left. \begin{aligned} C_{\text{harv}} &= C_{\text{harv}} + (0.05C_{\text{leaf}}) \\ C_{\text{leaf}} &= 0.95C_{\text{leaf}} \end{aligned} \right\} \text{ for DVI} > 1.5. \quad (8)$$

At the end of each growth time step (24 h), the amount of carbon in the leaves is related to leaf area index (L) by:

$$L = \frac{C_{\text{leaf}}}{f_C} \text{SLA} \quad (9)$$

where

$$\text{SLA} = \gamma (\text{DVI} + 0.06)^\delta \quad (10)$$

The values of γ and δ were determined by fitting the relationship to the paired values of DVI and SLA reported in ?.

The amount of carbon in the stem is related to the crop height by (?):

$$h = \kappa \left(\frac{C_{\text{stem}}}{f_C} \right)^\lambda \quad (11)$$

The values of κ and λ were determined by fitting the relationship to the paired values of h and C_{stem} at the Mead FLUXNET site (?).

Equations (??) and (??) are rearranged to derive the carbon content of leaves and stems, respectively, before each growth time step.

Because root biomass increases during the crop growing season the fraction of roots in each JULES soil layer varies according to the equation of ? which defines the fraction of roots at depth z as:

$$f = 1 - e^{-\frac{z}{a}} \quad (12)$$

230 where

$$a = d_r \left(\frac{C_{\text{root}}}{f_C} \right)^{r_{\text{dir}}} \quad (13)$$

where d_r is 0.5 for all crop types, and r_{dir} is a crop-specific parameter.

235 To ensure crop establishment, the growing season is curtailed if the sum of root, leaf, stem and reserve carbon falls below the initial seed carbon content (or zero) if the sowing date is determined dynamically.

2.3 Changes to JULES code structure

240 The standard version of JULES represents the land surface as a combination of up to 9 surface types including five plant functional types: broad-leaf trees, needle-leaf trees, C₃ grass, C₄ grass, shrubs, bare-soil, inland lakes, snow and ice. Surface fluxes of heat, moisture and momentum are determined independently for each tile before being combined to a single set of fluxes according to the relative fractions of each tile. Each crop type is considered as a different tile. Therefore, it is possible to simulate many crops or crop varieties at a site or grid box in a single integration of JULES, in addition to the standard five plant functional types. The parameters required to represent vegetation within JULES were extended to the crop tile(s). The values were copied across from the JULES default parameters for C₃ and C₄ grass, depending on the crop photosynthetic capacity (see Table ??).

245 The values of the parameters required in Eqs. (??)–(??) determine which crops are being simulated and can be varied according to different user requirements e.g crop species (e.g. maize or wheat), generic crop type (e.g. C₃ cereals) or cultivar (e.g. Soy bean PS123121 or Soy bean 21h321). Each parameter is described in Table ??.

255 Values for each parameter can be determined by calibration against relevant observational data such as leaf area index, biomass, yield from agricultural field stations. For this study such an exercise was not performed. Instead, suitable values were determined from either the literature or by tuning to fit site level data in order to establish a model version that could be evaluated at site and global scales.

3 Global simulation

3.1 Model set-up

To evaluate the potential of JULES-crop as a global gridded crop model, simulations for the period 1960 to 2010 were performed over the global domain. Four crop types were simulated; wheat, soybean, maize and rice. Parameter values are in Table ?? and were either taken from the crop science literature or calibrated as described below. Specifically, the values for the partition parameters $\alpha_{\text{root,stem,leaf}}$ and $\beta_{\text{root,stem,leaf}}$ and the specific leaf area coefficients γ and δ were calibrated against data in ?. The allometric coefficients κ and λ were determined by calibration against paired crop height and stem biomass data from FLUXNET sites. The cardinal temperatures (T_b , T_o , and T_m) were specified values in line with the range of values reported in the literature (see ? and ?). The effect of photoperiod was not included (by setting P_{crit} to 24) due to our method of determining thermal time between emerging and flowering (TT_{veg}) and thermal time between flowering and harvest (TT_{rep}) (see below).

The parameter r_{dir} was set to zero for all crop types which effectively removes the effect of increasing root carbon on the vertical distribution. Early tests of the model revealed that including an effect of increasing root carbon led to high levels of water stress at the start of the crop growing season leading to poor crop growth. Therefore, the effect was “turned-off”. The parametrisation was left in the model to allow other model users to experiment further with dynamic root growth.

The global model runs were driven by the CRU-NCEPv4 climate data extended to include 2012 (N. Viovy, personal communication, 2013) as used by the Global Carbon Project (?). This was regridded to a n96 grid (1.875 degrees longitude x 1.25 degrees latitude) and used with ancillaries from HadGEM2-ES (??) to evaluate the performance of the model in a Earth System Model set-up. A multi-layer canopy radiation scheme was used, accounting for direct/diffuse radiation components including sun-flecks ($\text{can_ran_mod} = 5$). The main run was from 1960 to 2010 and the spin up consisted of repeating the first ten years five times. The sowing dates were taken from ?, and a value for each land gridbox was obtained using nearest-neighbour extrapolation. The values of TT_{veg} and TT_{rep} were allowed to vary spatially and determined such

that, when used with the CRU-NCEP temperature climatology 1990–2000 and the ? sowing
285 date, the crop reached $DVI = 2.0$ at the ? harvesting dates, with $x = TT_{veg}/(TT_{veg} + TT_{rep}) =$
0.5, 0.45, 0.6, 0.6 for soybean, maize, wheat, rice respectively. Photoperiod sensitivity was not
considered. This is because including it would have made calculating TT_{veg} and TT_{rep} almost
impossible, because three variables would need calibrating at each grid cell (total TT, critical
290 photoperiod, and sensitivity to photoperiod) from one observation (growing season duration).
For comparison a control run was completed using the same model set-up but with the crop code
switched off. This run is used to assess performance against the standard land surface scheme
in the Met Office Hadley Centre Earth System Model – HadGEM2-ES.

Figure ?? shows the planting date of ? and the derived maps of TT_{veg} and TT_{rep} . ? derived
305 gridded planting dates from national or district level reported planting dates which are given
in months rather than days. Therefore, there is little spatial or temporal variation in the sowing
date which might well be expected due to variations in local climate and management practices.
However, the data serves a purpose in global modelling studies by providing an approximate
start point for the growing season at the right time of year. Our method of calculating the crop
thermal time requirements produces considerable spatial variability which is determined in re-
300 lity by variation in the choice of crop cultivar chosen. Other global crop modelling studies have
approached the issue of specifying these requirements at the global scale in different ways. ?
chose three sets of thermal time requirements and applied them over the globe allowing for
assessment of which were most suitable after the simulations, whereas ? related thermal time
requirements (calculated from ? in a similar manner to this study) to the annual accumulated
305 thermal time and then used that relationship to determine thermal time requirements under fu-
ture climate. The approach in this study was chosen as the simplest and most likely to achieve
growing seasons of lengths close to observed. Due to the absence of a vernalisation parametrisation
in the model only spring wheat was considered. The crop fractions were taken from ?
and re-gridded to the n96 HadGEM2-ES resolution. ? provide observations in the year 2000
310 which were used to describe the crop coverages for the whole integration period due to a lack
of available data sets covering this time period.

3.2 Evaluation

The simulated grid box annual yield for each crop averaged over the 50 years is shown in Fig. ?? along side global gridded observations for circa 2000 (?). Fig. ?? shows that in general the model is under-estimating yields in arid, irrigated regions and over-estimating them in tropical regions. In particular simulated maize yields are significantly larger than observations in tropical regions. Given that the model does not include any information on the yield gap (the difference between actual farm level yield and potential yield) or important land management such as irrigation the spatial variability of model output should not be too closely compared to that of observed yield. Instead, a greater appreciation of model performance can be gained from examining the year to year fluctuations in yield, given that the effects of changes in management and technology materialise over several years.

Figures ?? and ?? show the simulated global and country level yield for wheat, soybean, maize and rice between 1960–2008 compared to the reported yields of ?. Simulated global yield was determined by multiplying the simulated annual maximum yield at each grid cell by the observed harvested area from ? regridged to the HadGEM2-ES spatial resolution. This grid cell estimate of production was summed over all grid cells to produce an estimate of global production which was then divided by the total harvested area to provide an estimate of global yield. Grid cell yields were determined from the annual maximum value of C_{harv} which was multiplied by 2 to convert from carbon mass to total biomass, by 1.16 to account for grain moisture content, and by 10 to convert from kg m^{-2} to Mg ha^{-1} . Not all grid cells were included in the analysis. Cells were excluded if the annual maximum DVI was less than 1.5 which was possible if the growing season was curtailed if $\text{LAI} > 15$ or $t_{\text{soil},2} < T_{\text{bse}}$. A similar analysis was conducted to determine country level yields with averages taken over all gridcells within a particular country.

Country yields observations were de-trended for comparison with model output. This is because the increasing trend in yields observations over the last fifty years is due to improvements in agricultural technology and management and increasing atmospheric carbon dioxide. This trend is not reproduced by the model as these processes were not represented in our set-up.

340 The average simulated yield for maize is over-estimated however, the model does a reason-
able job of reproducing the inter-annual variability at the global ($r = 0.48$) and country scale
(Fig. ?? a) although there is a tendency to simulate larger variability than observed. For soy-
bean, average yield is again much greater than observed but year on year variability is correlated
with observations ($r = 0.37$) providing some confidence in the model's ability to simulate the
observed response of soybean yield to climate. Regionally, in countries such as USA ($r = 0.39$)
345 and India ($r = 0.52$) JULES-crop is able to reasonably capture inter-annual variability of yields
(Fig. ?? b). For rice, yield levels are higher than reported, variability is overestimated and
not correlated with observations ($r = 0.24$). At the country level, model simulations in India
($r = 0.57$) correlate with observations (Fig. ?? c). The average simulated yield level for wheat
is similar to the most recent observations but when comparing the year to year fluctuations in
350 yield, the correlation between simulated and observed is low ($r = 0.019$). Because JULES-crop
only simulates spring wheat then the comparison to reported wheat yields is slightly unfair
given that the majority of wheat produced globally is from winter varieties. It is encouraging
that the best agreement between simulated and observed yield fluctuations at the national level
is for Turkey ($r = 0.46$) and Australia ($r = 0.53$), in which spring wheat varieties dominate.

355 For all crops there is a tendency for JULES-crop to simulate larger variability than observed.
This may in part be explained by the lack of certain processes in the model (particularly those to
do with land management). For example not including a representation of irrigation in the model
may explain why the model predicts lower yields than observations as irrigation would act to
reduce the extent of crop failure in drought years. The model also does not include the impacts
360 of pests and disease which may reduce overall yields in some years. Importantly, the model
does not as yet include a nitrogen cycle which may reduce overall GPP bringing the simulations
in line with observations. This may also explain why there are strong deviations between the
magnitude of observed and modelled yield in tropical countries where climatic conditions for
growth are good in the absence of the limitations described above.

365 For some countries simulations of yield capture the magnitude and variability of observations.
In other countries the model reproduces the variability in yield but over-predicts the magnitude.
There are also countries where the model performs poorly in simulating both variability and

magnitude. This variety of results is due in part to the use of generic parametrizations for global model runs which is a limitation of this type of Earth System Model set-up. By using parameters that do not vary spatially we can not fully represent the range of crop varieties that are found globally.

To evaluate the impact of including the crop parametrisation on JULES, output from the simulation with crops included is compared to a control simulation of the standard JULES configuration with grass plant functional types taking the land fraction of crops. Impacts on the land surface will be mostly mediated via direct changes to the vegetation structure and also via indirect effects on state variables, most obviously the soil moisture content. To begin to examine the potential for impact, the changes to a key vegetation variable leaf area index (LAI) are shown in Fig. ?? for four major crop producing countries. To produce the country averages, grid cell LAI are combined by weighting by the grid cell contribution to total country crop area. In the USA and China each crop growing season occupies the similar set of summer months, whereas for India and Brazil the wheat cropping season is distinct from the other three crops. Peak LAI is greatest in Brazil and lowest in China which is most likely a reflection of the absence of irrigation in the model and the relative abundance of rainfall in each country. In comparison to the standard JULES configuration the addition of crops adds a seasonality to LAI as there is no default seasonality to vegetation characteristics in JULES. The annual variation of crop LAI is dampened when aggregated with the other plant functional types which explains the non-zero LAI in the non-growing season in the JULES-crop simulation. Fig. ?? shows that the inclusion of crops alters the gridbox net primary production (NPP) in terms of the timing of peak fluxes. There are also lower fluxes in winter due to the more realistic treatment of LAI at this time. Therefore, including a representation of crops in JULES may help improve the seasonality of LAI and which affects carbon fluxes.

Figure ?? shows that the impact of these differences in vegetation size during the year is greatest for the surface moisture flux and sensible heat flux rather than the components of the radiation balance. The largest impacts are on the sensible heat flux towards the end of the crop growing season which is higher with the inclusion of crops. For India there is a concomitant decrease in the surface moisture flux implying that the total available energy at the surface

is unaltered but is partitioned differently between sensible and latent heat fluxes. The impact of JULES-crop on the energy balance is however minimal. In this configuration the model is forced by prescribed meteorology at screen height. This has the tendency to damp the model in comparison to a full atmospheric simulation in which the boundary layer state is able to evolve. It may therefore be expected that a GCM may be more sensitive to changes in the surface state.

4 Site simulation

4.1 Model set-up

To further understand the impact of adding crops to JULES, site level simulations were also performed. Evaluation was restricted to sites at which crops were grown and with availability of suitable meteorological data to drive the model and biological and flux data for evaluation. The sites selected were all in the USA; Mead in Nebraska (?), and Bondville and Fermi, Illinois. For each site three simulations were performed; the standard configuration of JULES, standard JULES with the existing phenology parametrisation turned on, and the full JULES-crop parametrisation. For the JULES-crop simulation the fractional coverage of the relevant crop type was set to 1 with all other functional types set to 0. For the JULES (non-crop) simulations, the fractional coverage of the relevant grass functional type (i.e. C₃ grass for soybean, C₄ for maize) was set to 1. All crop parameters were prescribed the same value as in the global simulations. The sowing date, and thermal time requirements were taken from the relevant grid cell for each site.

4.2 Evaluation

Figures ?? and ?? compares JULES-crop simulations for the soybean crop type with standard JULES C₃ grass plant functional type with and without phenology, and with observations where available. The crop parametrisation captures the evolution of leaf area index (LAI) and canopy height across the season, although the model underestimates these growth variables. The model also simulates lower gross primary production (GPP) fluxes compared to observations which

leads to an under estimation of crop yields. The standard C₃ grass with phenology configuration of JULES also simulates growth and decay of vegetation cover but over a longer period of time than the observed growing season. Without the phenology routine the LAI is set to the default
425 for C₃ grass of 2.0 all year. Interestingly, the more realistic simulation of vegetation cover does not lead to improved simulation of surface fluxes. At all sites similar characteristics of the simulations are evident. During winter all three configurations simulate similar latent and sensible heat fluxes in line with observations (Fig ??) . Towards the start of the growing season the standard configuration of JULES with constant LAI = 2.0 overestimates latent heat flux due
430 to an unrealistically large vegetation coverage. The simulations with phenology and crops have lower vegetation cover and simulate lower latent heat flux but are still noticeably greater than observations. At around the peak of crop cover all simulations underestimate the latent heat flux and over estimate the sensible heat flux due to lower simulated LAI compared to observations.

Site level simulations for the maize crop type are shown in Figures ?? and ??. The crop
435 parametrisation is reasonably successful in capturing LAI and canopy height of maize at all evaluation sites although again does not simulate maximum values. Again GPP and yields are lower than observed although the seasonal pattern of GPP is close to observations. Overall, model simulations broadly capture the patterns of latent and sensible heat fluxes although again there are no major improvements in model performance with the explicit inclusion of crops.
440 At Fermi in 2006 the crop specific simulation captures the observed evolution of LAI reasonably well with peak LAI slightly closer to observations than the standard JULES simulations. However, this again does not improve the simulation of heat fluxes.

All model configurations overestimate the partitioning of energy in to latent heat before the
445 growing season begins and underestimate it during the crop growing season, despite widely varying LAI values. This could be due to the relatively weak LAI-surface conductance relationship found in JULES (?). This is reflected in the low sensitivity to LAI between fixed and grass phenology. In these simulations we would therefore not expect a large response to an alternative representation of crop LAI phenology. This comparison serves as a reminder that improving the realism of a model may not guarantee improved performance in the model in other aspects. The
450 results also show that JULES (crop and standard configurations) is not able to capture the mag-

455 nitude of observed GPP fluxes. This suggests that using the standard physiological parameters for C₃ and C₄ grasses is not appropriate when representing crops particularly as JULES does not include nitrogen fertilization explicitly. Tuning of parameters that describe leaf nitrogen for example may improve fluxes of GPP and hence overall yields. It is worth also noting that the parameters used for the crop model in the site simulations are from the global set-up and hence are probably not optimal for site simulations.

5 Discussion and Conclusions

460 When designing JULES-crop we took a flexible approach in acknowledgement of the different requirements of the science community. This means the model can be used to address a range of science questions for example (a) to assess global climate impacts on crop functional types over long integrations with climate model output, (b) to represent a number of crop cultivars of the same crop type at the site scale forced with weather observations and (c) to assess how crops may impact on biogeophysical feedbacks to climate including albedo, partitioning of turbulent fluxes and seasonality of LAI. In this paper we present results from a generic, crop 465 functional type parametrisation implemented at both global and site scale to show how this model performs in an Earth System Model context. Having the aim of generality necessarily means that the model loses out in terms of specificity. However, with further effort it should be possible to tailor the model set-up for more specific applications but with the requirement that attention is given to the choice of parameter values. Default values are provided here as a starting point for model development and initial evaluation. 470

These results demonstrate the importance of evaluating the performance of JULES-crop in a holistic sense, assessing both its ability to simulate land surface fluxes in addition to crop growth and development dynamics and to recognise that identified biases in performance are the result of the combined JULES-crop model, not just the added crop component. Adding a crop 475 parametrisation has increased the complexity of JULES. However, this has not led to an immediate improvement in the model's simulation of surface fluxes, at least at the measurement sites

examined. More effort needs to go into developing the parameter sets for crops within JULES particularly the existing set of plant functional type parameters which control productivity.

480 Comparing the regional patterns of yield to observations gives useful insight into the existing limits of the model. It is clear that some important processes are missing particularly irrigation (although this model development will shortly be submitted for release). Developing a nitrogen cycle for JULES (model development also in progress) should also improve the model simulations as introducing nitrogen limitation has been shown to reduce overall productivity in earth system models (?). JULES-crop will still exclude many management factors which affect regional yields. ? estimated global yield gaps and showed they were greatest in tropical regions. Although not directly comparable with our simulations this study shows us that JULES-crop simulations are likely to over-estimate yields in tropical regions compared with observations. However, we have deliberately not introduced a yield gap adjustment as it would not be physically based and as such would be difficult to apply to future simulations. It is however, important to capture regional differences due to management as they will effect patterns in productivity and hence feedbacks to the climate. In an earth system model context it is better to represent these management processes explicitly were possible as they effect not only crop growth but also may well influence the local climate directly (e.g. irrigation (?)).

495 As a yield simulation model, there are encouraging signs that JULES-crop can simulate variability in yield associated with climate fluctuations. However, it is clear that JULES-crop over-estimates the magnitude of this variability. Whilst the absence of irrigation is most likely a contributing factor to the over-estimation of yield variability, the implication that the model is too sensitive to changes in environmental conditions should also be investigated further.

500 Including crops in JULES gives a more realistic seasonal cycle of leaf area index which affects the seasonality of carbon fluxes (timing of peak flux and lower winter fluxes). This was seen at both the global and site level. The impact of crops on the energy balance was to alter the partitioning of latent and sensible heat fluxes particularly in winter which led to small impacts on temperature in some countries. These impacts were marginal at the country and site scale despite quite large differences in LAI. It is possible that the relationship between LAI and evaporation is too weak in JULES (?) which may explain why more realistic representation of

LAI did not improve the energy fluxes. We may expect a higher sensitivity in fully coupled atmosphere model.

Crop production systems are by their very nature heavily influenced by humans. This represents a challenge to the JULES model which, to date, assumed vegetation to be static and, within each vegetation tile, homogeneous by the use of global constants for parameter values. The level to which this approach can be extended to crops is limited. Whilst some processes might be considered fundamental (i.e. photosynthesis) others can vary from place to place for the same crop (e.g. sensitivity of development rate to daylength). Further still, human interference can alter the fundamental process, for example the application of fertiliser to increase leaf nitrogen contents impacting on photosynthesis. For applications of JULES-crop that rely on accurate yield simulations the inclusion of either a yield gap variable, or the factors that determine it such as fertilizer applications, pest control, soil fertility, should be a priority for future model development. Inclusion of winter wheat is also high priority for JULES-crop. This is important for use of JULES-crop as a yield simulation model but also an earth system model as the additional presence of vegetation cover from autumn to spring would impact on surface characteristics (albedo, heat capacity etc).

Acknowledgements. This work was supported by the Joint DECC/Defra Met Office Hadley Centre Climate Programme and the National Centre for Atmospheric Science. Richard Betts was also supported by the University of Exeter and the EU High-End cLimate Impacts and eXtremes (HELIX) project.

Table 1. Crop model parameters used in JULES-crop.

Parameter	Unit	Equation	Description
T_b	$^{\circ}\text{C}$	Eq.(??)	Base temperature
T_o	$^{\circ}\text{C}$	Eq.(??)	Optimum temperature
T_m	$^{\circ}\text{C}$	Eq.(??)	Maximum temperature
TT_{emr}	$^{\circ}\text{C d}$	Eq.(??)	Thermal time between sowing and emergence
TT_{veg}	$^{\circ}\text{C d}$	Eq.(??)	Thermal time between emergence and flowering
TT_{rep}	$^{\circ}\text{C d}$	Eq.(??)	Thermal time between flowering and maturity/harvest
P_{crit}	h	Eq.(??)	Critical photoperiod
P_{sens}	h^{-1}	Eq.(??)	Sensitivity of development rate to photoperiod
r_{dir}	–	Eq.(??)	Coefficient determine relative growth of roots vertically and horizontally
α_{root}	–	Eq.(??)	Coefficient for determining partitioning
α_{stem}	–	Eq.(??)	As above
α_{leaf}	–	Eq.(??)	As above
β_{root}	–	Eq.(??)	As above
β_{stem}	–	Eq.(??)	As above
β_{leaf}	–	Eq.(??)	As above
γ	$\text{m}^2 \text{kg}^{-1}$	Eq.(??)	Coefficient for determining specific leaf area
δ	–	Eq.(??)	As above
τ	–	Eq.(??)	Fraction of stem growth partitioned to C_{resv}
f_C	–	Eqs.(??), (??), (??)	Carbon fraction of dry matter
κ	–	Eq.(??)	Allometric coefficient which relates C_{stem} to h
λ	–	Eq.(??)	As above

Table 2. Crop model variables in JULES-crop.

Variable	Unit	Equation	Description
New variables			
T_{eff}	$^{\circ}\text{C}$	Eqs.(??), (??)	Effective temperature
DVI	–	Eqs.(??), (??), (??), (??)	Development Index
C_{leaf}	kg C m^{-2}	Eqs.(??), (??), (??), (??)	Leaf carbon pool
C_{stem}	kg C m^{-2}	Eqs.(??), (??), (??)	Stem carbon pool
C_{root}	kg C m^{-2}	Eqs.(??), (??), (??)	Root carbon pool
C_{harv}	kg C m^{-2}	Eqs.(??), (??), (??)	Harvested organ carbon pool
C_{resv}	kg C m^{-2}	Eqs.(??), (??)	Stem reserve carbon pool
p_{leaf}	–	Eqs.(??), (??)	Fraction of NPP partitioned to C_{leaf}
p_{stem}	–	Eqs.(??), (??), (??)	Fraction of NPP partitioned to C_{stem}
p_{root}	–	Eqs.(??), (??)	Fraction of NPP partitioned to C_{root}
p_{harv}	–	Eqs.(??), (??)	Fraction of NPP partitioned to C_{harv}
P	h	Eq.(??)	Photoperiod (day length)
RPE	–	Eqs.(??), (??)	Relative Photoperiod Effect
Existing variables			
T	$^{\circ}\text{C}$	Eq.(??)	1.5 m temperature on each tile
L	$\text{m}^2 \text{m}^{-1}$	Eq.(??)	Leaf area index
SLA	$\text{m}^2 \text{kg}^{-1}$	Eqs.(??), (??)	Specific Leaf Area
h	m	Eq.(??)	Canopy Height
Π	kg C m^{-2}	Eqs.(??), (??)	Net primary productivity
A_c	kg C m^{-2}	Eq.(??)	Net carbon assimilation
R_{dc}	kg C m^{-2}	Eq.(??)	Canopy dark respiration

Table 3. JULES plant functional type parameters extended to represent crop types wheat, soybean, maize and rice.

Crop type	Wheat	Soybean	Maize	Rice
$c3$	1	1	0	1
d_r	0.5	0.5	0.5	0.5
dq_{crit}	0.1	0.1	0.075	0.1
f_d	0.015	0.015	0.025	0.015
f_0	0.9	0.9	0.8	0.9
n_{eff}	8.00×10^{-4}	8.00×10^{-4}	4.00×10^{-4}	8.00×10^{-4}
$n_1(0)$	0.073	0.073	0.06	0.073
σ_1	0.032	0.032	0.025	0.032
T_{low}	0	0	13	0
T_{upp}	36	36	45	36

Table 4. Parameter values used to represent crop types wheat, soybean, maize and rice. See Table?? for parameter definitions.

Crop type	Wheat	Soybean	Maize	Rice
T_b	0	5	8	8
T_o	20	27	30	30
T_m	30	40	42	42
TT_{emr}	35	35	80	60
TT_{veg}		See Fig.??		
TT_{rep}		See Fig.??		
P_{crit}	24	24	24	24
P_{sens}	0.00	0.00	0.00	0.00
r_{dir}	0.0	0.0	0.0	0.0
α_{root}	18.5	20.0	13.5	18.5
α_{stem}	16.0	18.5	12.5	19.0
α_{leaf}	18.0	19.5	13.0	19.5
β_{root}	-20.0	-16.5	-15.5	-19.0
β_{stem}	-15.0	-14.5	-12.5	-17.0
β_{leaf}	-18.5	-15.0	-14.0	-18.5
γ	27.3	25.9	22.5	20.9
δ	-0.0507	-0.1451	-0.2587	-0.2724
τ	0.40	0.18	0.35	0.25
f_C	0.5	0.5	0.5	0.5
κ	1.4	1.6	3.5	1.4
λ	0.4	0.4	0.4	0.4

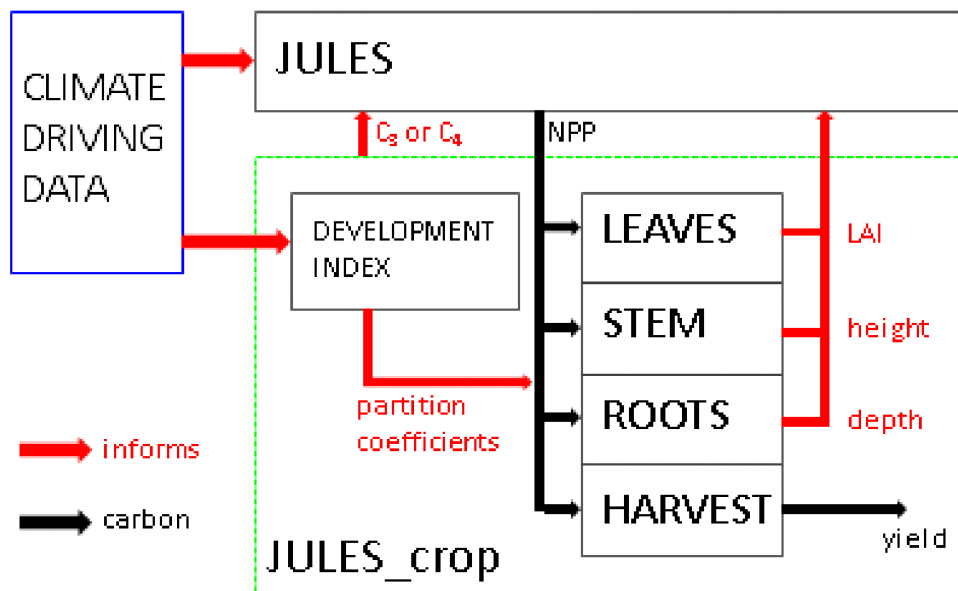


Figure 1. Schematic of JULES-crop

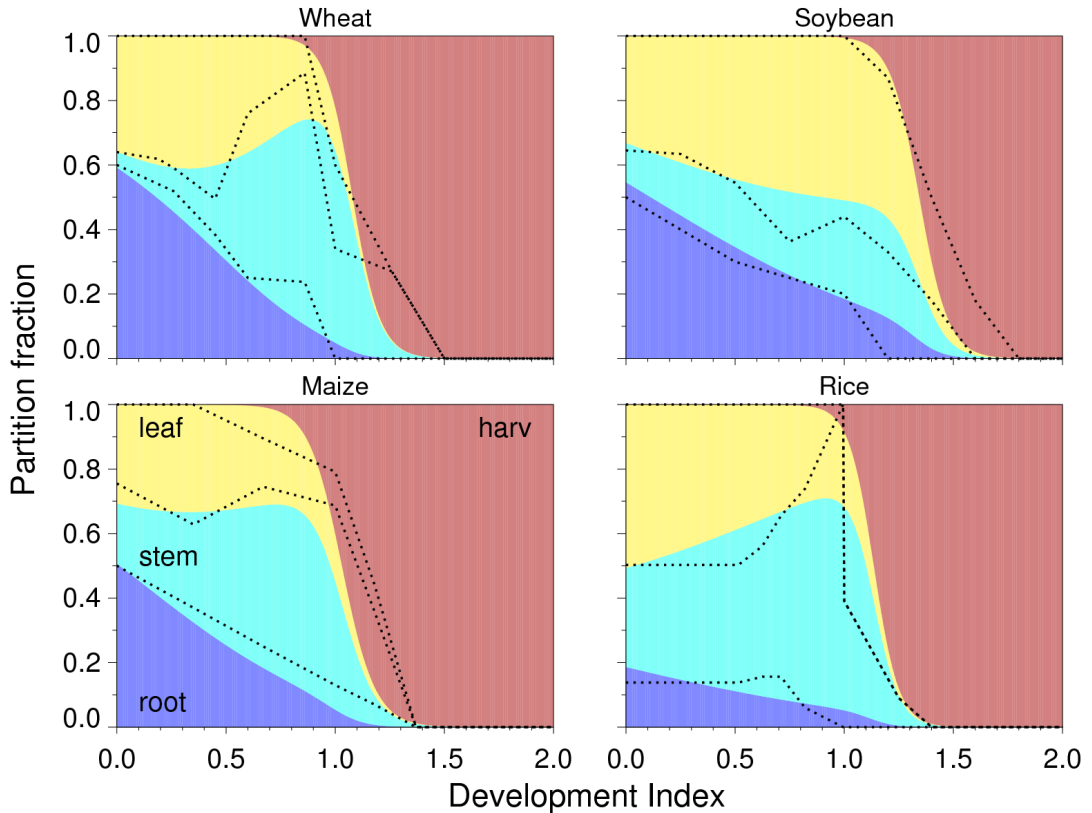


Figure 2. Fraction of daily accumulated net primary productivity partitioned to roots (purple), stems (blue), leaves (yellow) and harvested parts (red) of the crop as a function of development index (DVI; 0=emergence, 1=flowering, 2=maturity) for wheat, rice, soybean and maize.

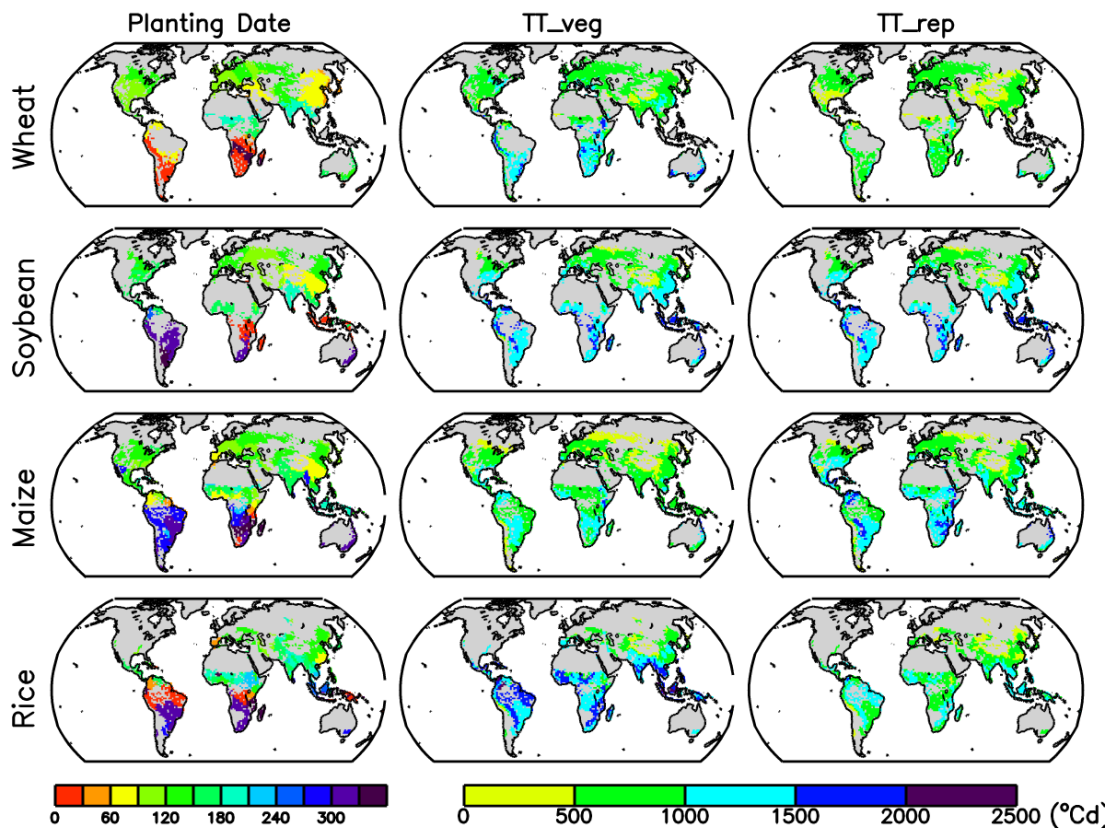


Figure 3. Global distribution planting date from ?, interpolated to NCEP grid, and the thermal time from emergence to flowering (TT_{veg}) and from flowering to harvest (TT_{rep}) for each crop type. See text for details of calculation.

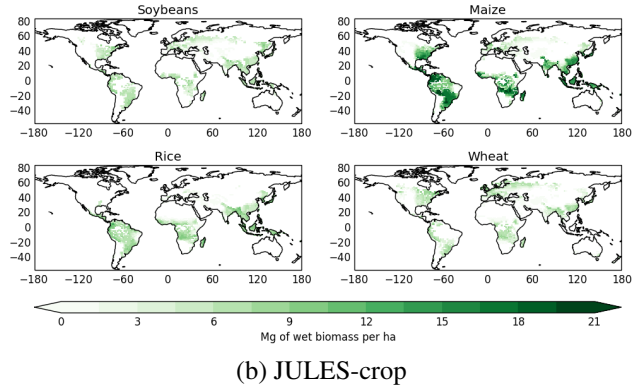
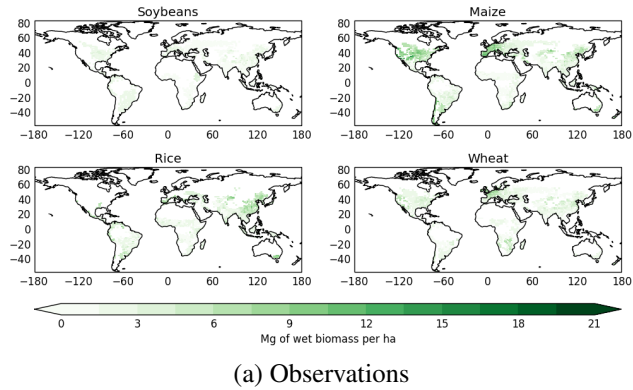


Figure 4. Global distribution of average wheat, soybean, maize and rice yield (Mg per ha) in a) observations (?) regridded to n96 resolution and b) JULES-crop global simulations (assuming a moisture content of 16% and a carbon fraction of 0.5)

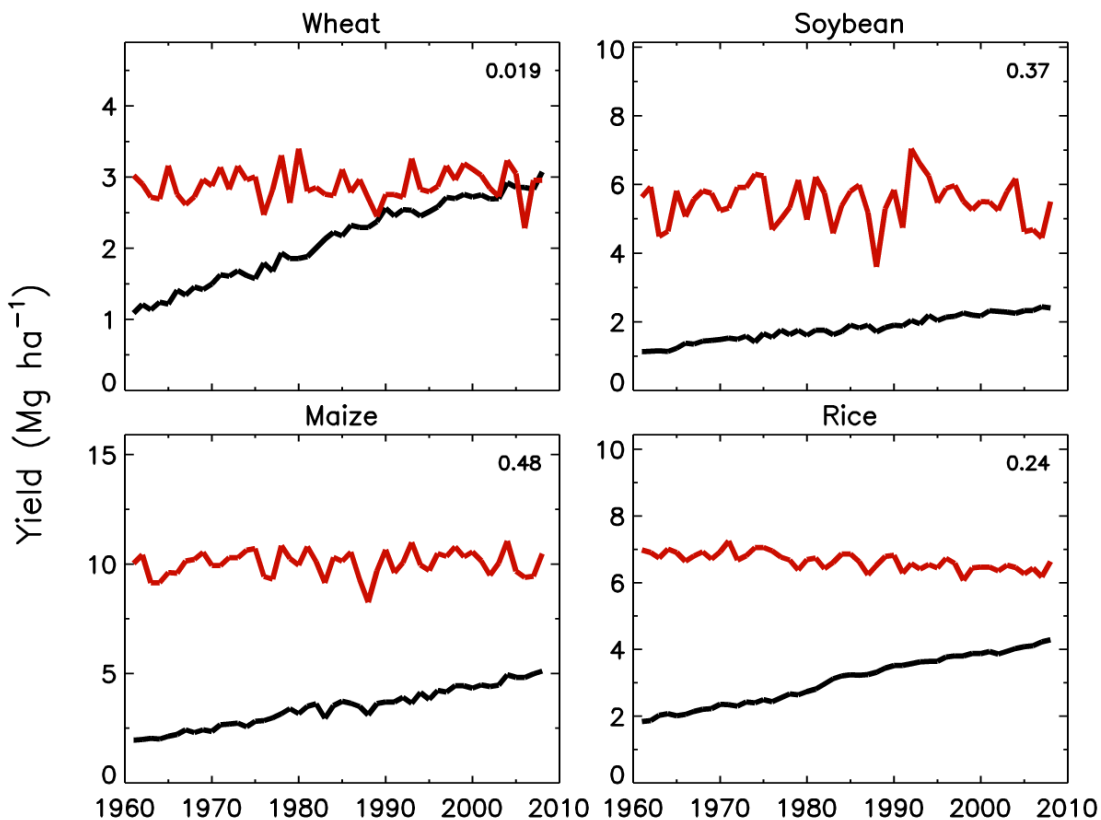


Figure 5. Simulated (red) and observed (black) global yield of wheat, soybean, maize and rice between 1961-2008. Values in the top right are results of a correlation between observations and JULES-crop simulations

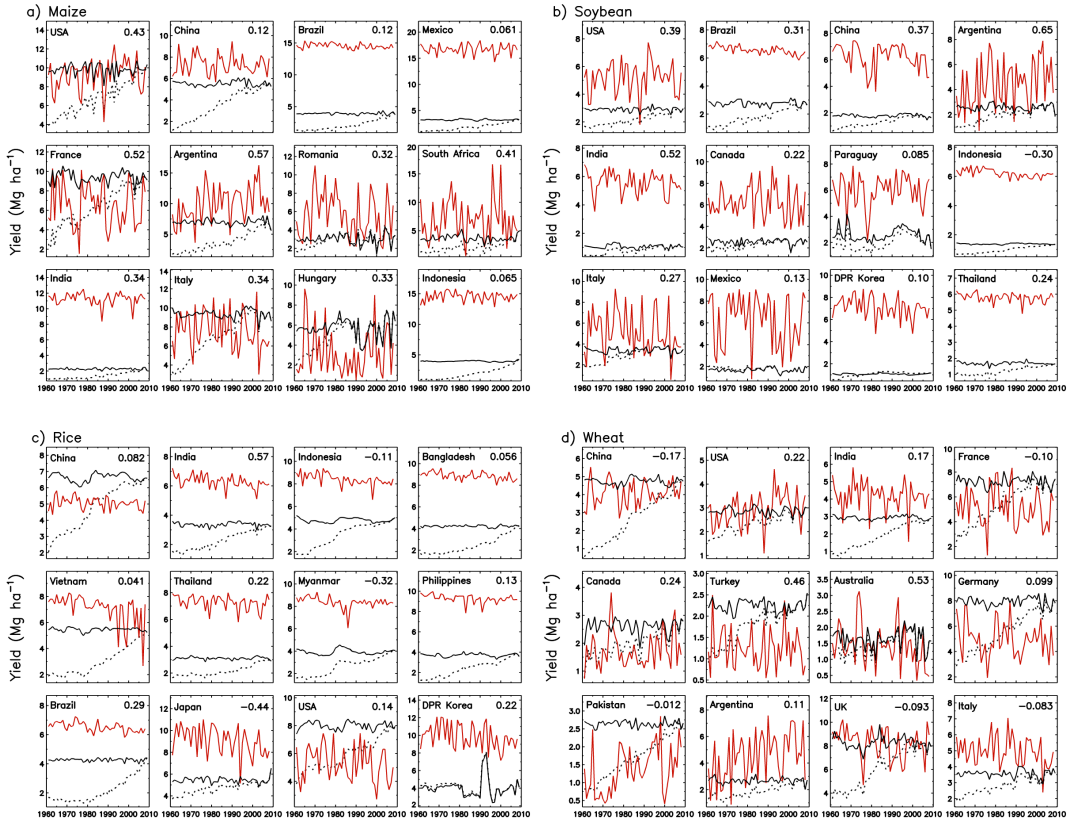


Figure 6. Simulated (red), observed (black dashed) and de-trended observed (black) country level yields of a) Maize, b) Soybean, c) Rice and d) Wheat between 1961-2008. Values in the top right are results of a correlation between de-trended observations and JULES-crop simulations

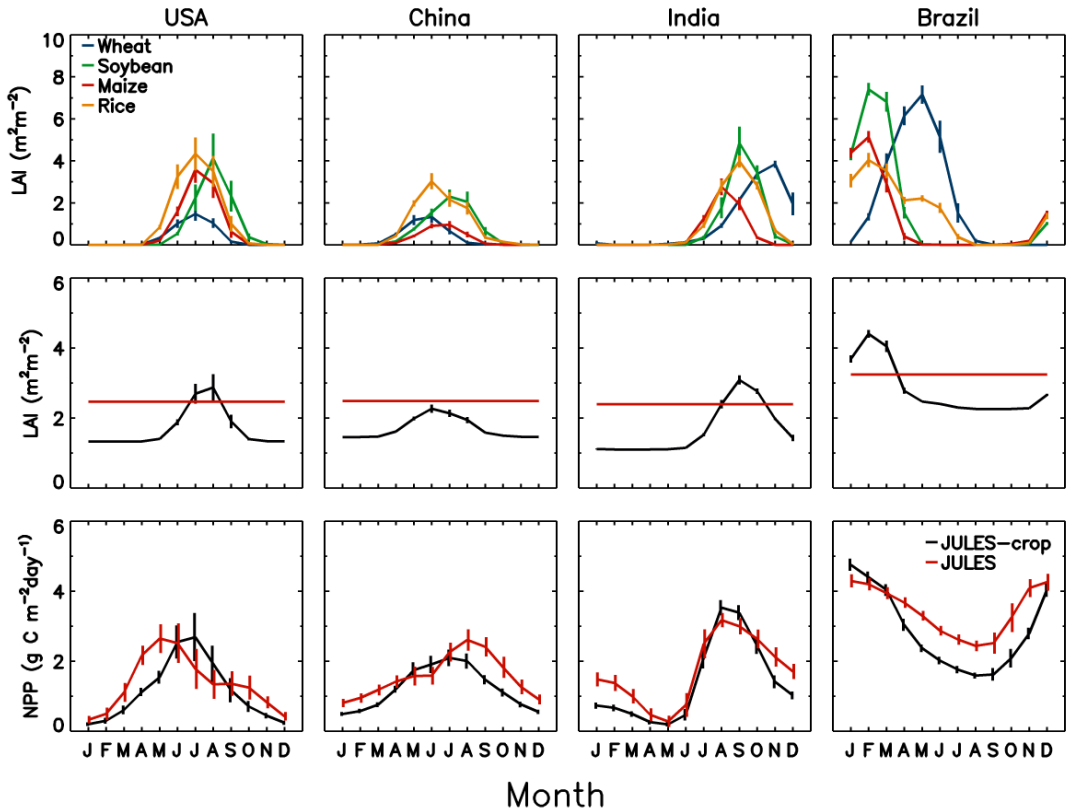


Figure 7. Country crop area weighted annual cycle of crop type (top) and grid-box mean (middle) leaf area index (LAI) and grid-box mean (bottom) Net Primary Production (NPP). Area averages weighted by crop area in top panel, and total plant functional type area in middle and bottom panels. Vertical bars indicate standard deviation of monthly values.

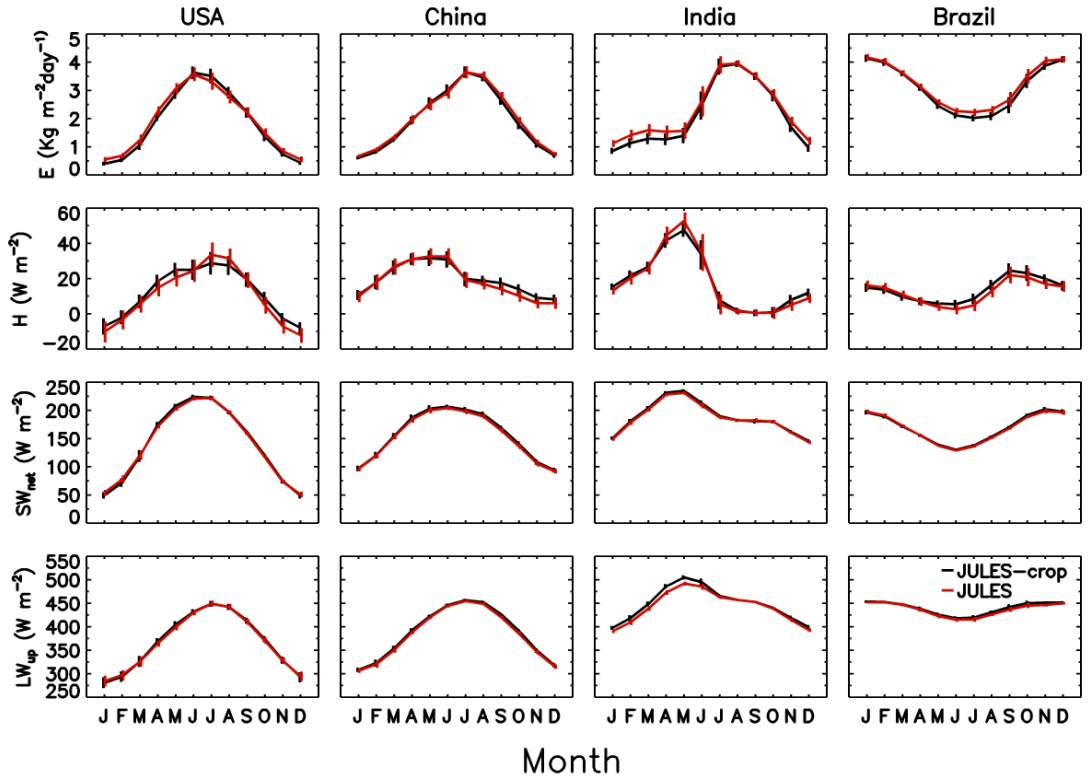


Figure 8. Country crop area weighted average mean annual cycle of surface moisture flux (E), sensible heat flux (H), net short wave radiation (SW_{net}) and upward long wave radiation (LW_{up}) from JULES-crop simulation (red) and standard JULES simulation (black) forced with CRU-NCEP meteorological driving data. Vertical bars indicate standard deviation of monthly values.

Soybean

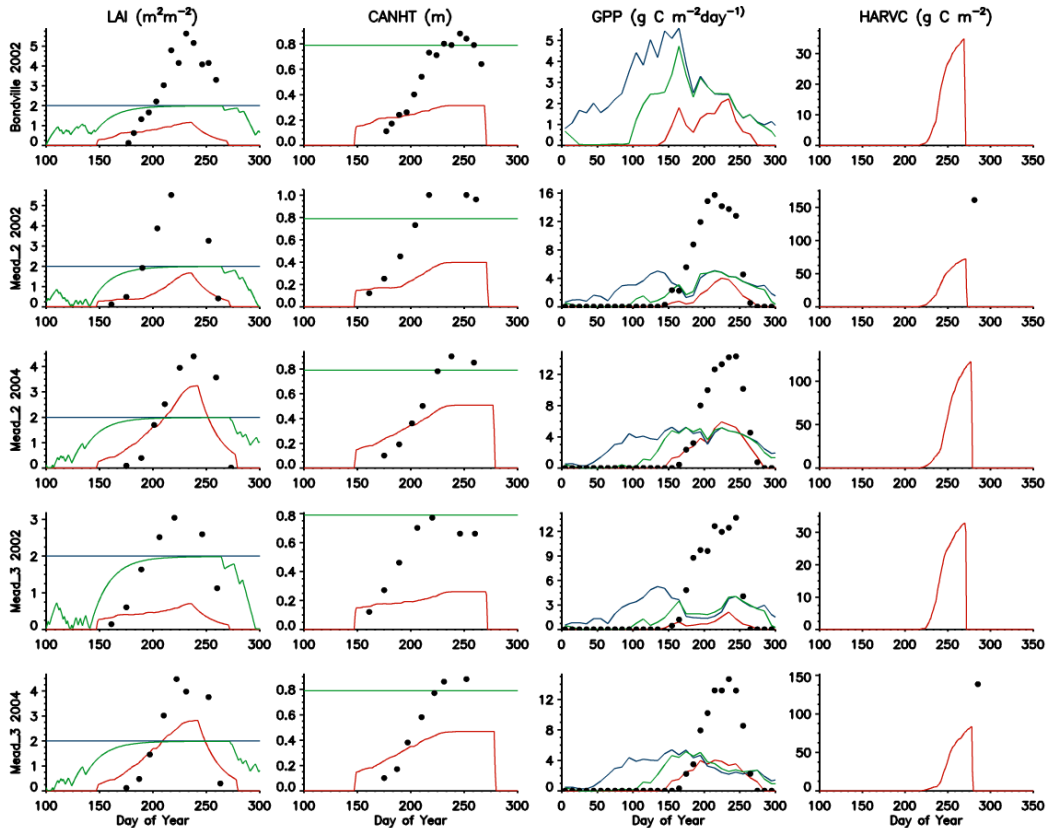


Figure 9. Simulated (solid lines) and observed (dots) Leaf Area Index (LAI), Canopy Height (CANHT), Gross Primary Production (GPP) and Harvest Carbon (HARVC) at a range of fluxnet sites and years. Simulations performed with JULES-crop crop type Soybean (red), standard JULES C₃ grass plant functional type with phenology (green), and standard JULES C₃ grass plant functional type without phenology (blue).

Soybean

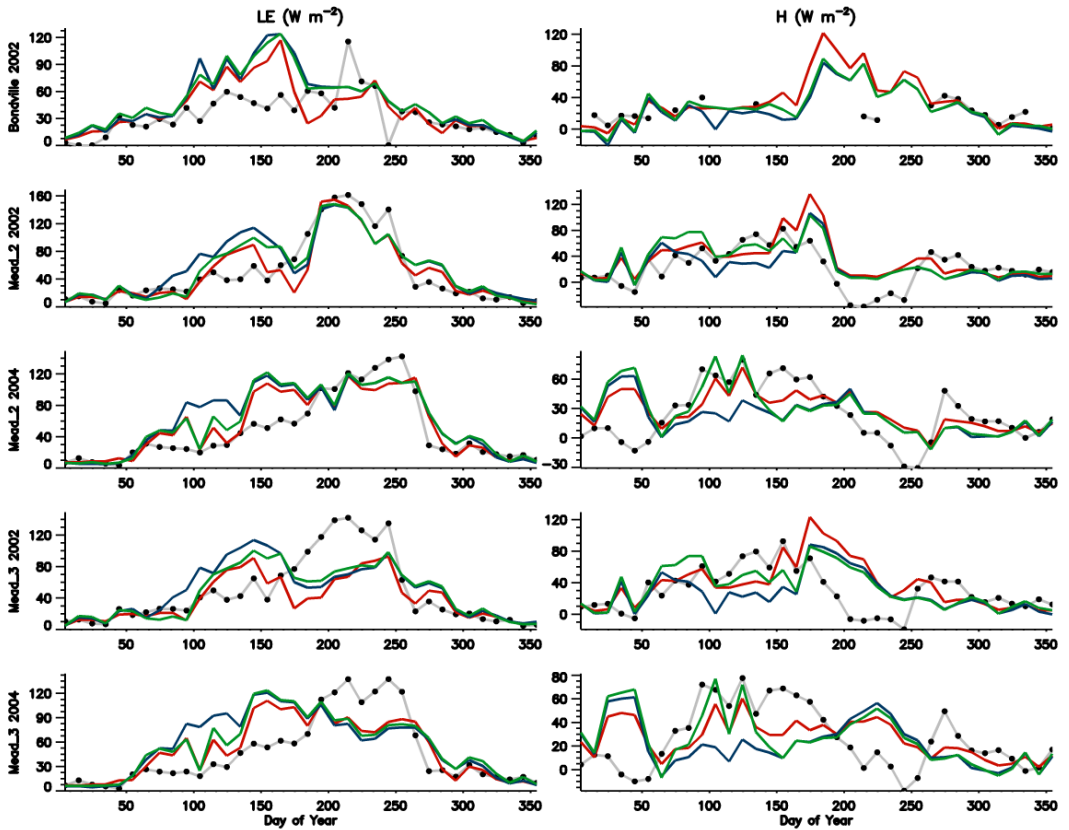


Figure 10. Simulated (solid lines) and observed (dots) Latent (LE) and Sensible (H) heat fluxes at a range of fluxnet sites and years. Simulations performed with JULES-crop crop type Soybean (red), standard JULES C₃ grass plant functional type with phenology (green), and standard JULES C₃ grass plant functional type without phenology (blue).

Maize

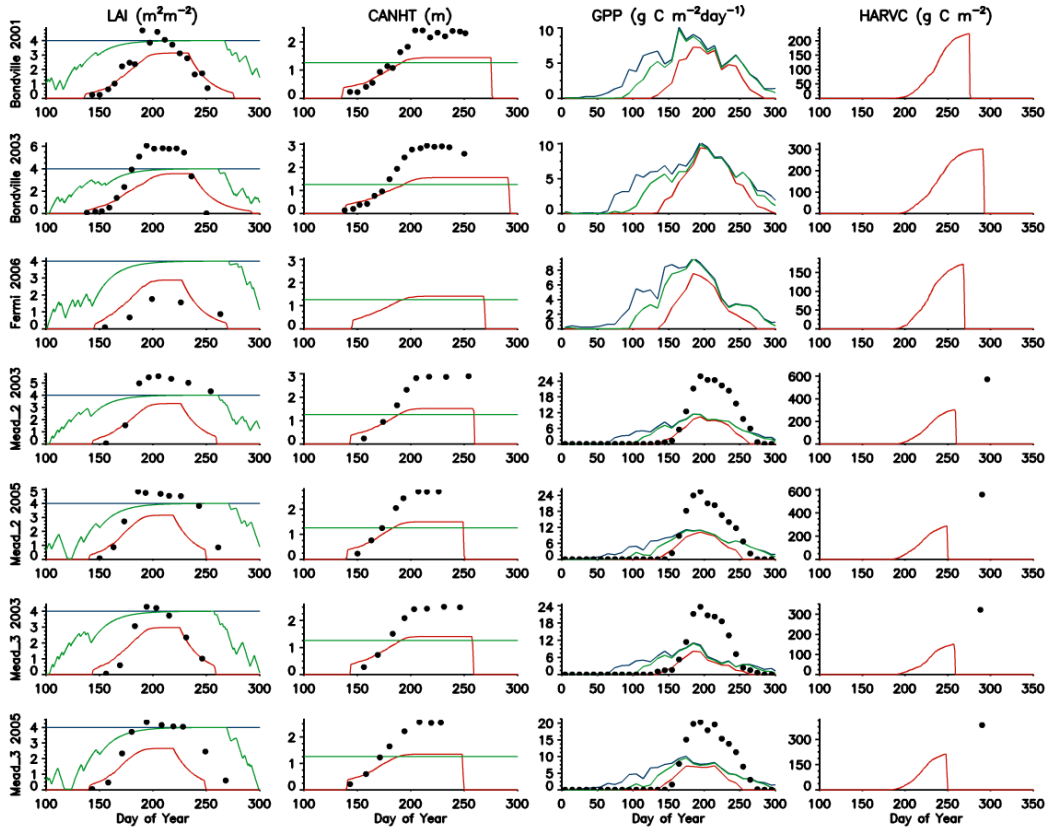


Figure 11. Simulated (solid lines) and observed (dots) Leaf Area Index (LAI), Canopy Height (CANHT), Gross Primary Production (GPP) and Harvest Carbon (HARVC) at a range of fluxnet sites and years. Simulations performed with JULES-crop crop type Maize (red), standard JULES C₃ grass plant functional type with phenology (green), and standard JULES C₃ grass plant functional type without phenology (blue).

Maize

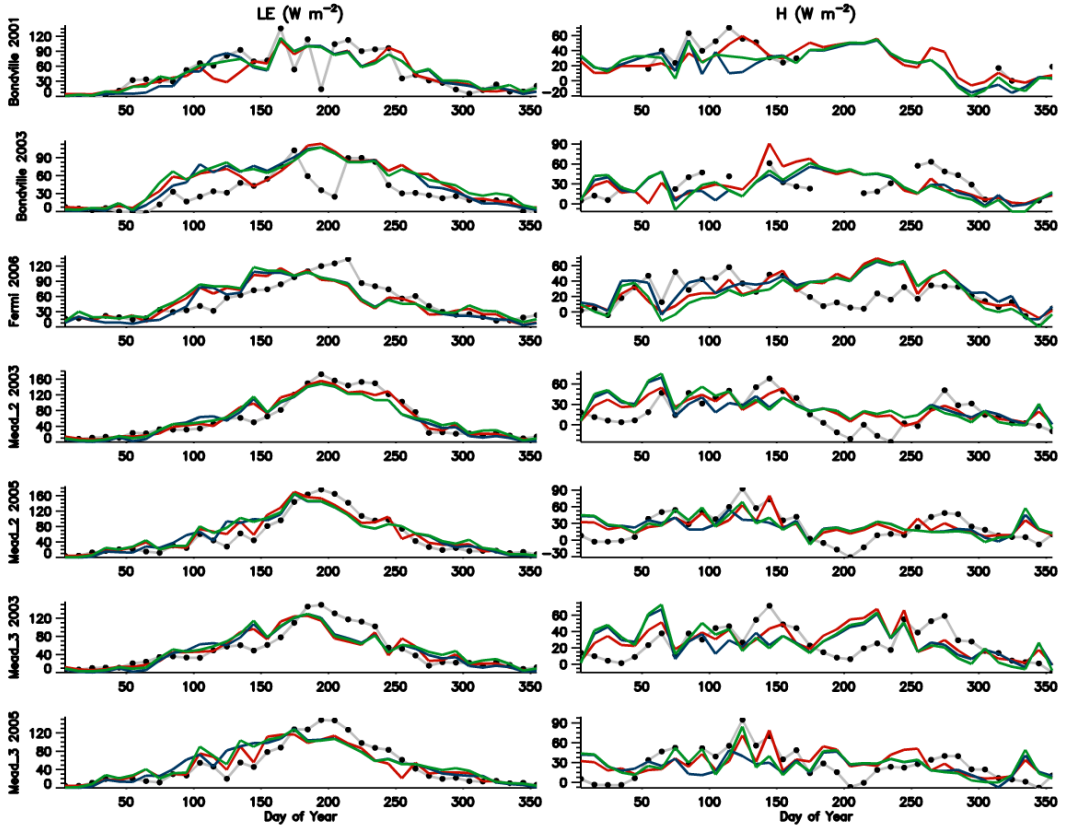


Figure 12. Simulated (solid lines) and observed (dots) Latent (LE) and Sensible (H) heat fluxes at a range of fluxnet sites and years. Simulations performed with JULES-crop crop type Maize (red), standard JULES C₃ grass plant functional type with phenology (green), and standard JULES C₃ grass plant functional type without phenology (blue).