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Comment

## ***Interactive comment on “JULES-crop: a parametrisation of crops in the Joint UK Land Environment Simulator” by T. Osborne et al.***

**T. Osborne et al.**

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Received and published: 5 February 2015

AC: This is a comment in reponse to reviewer's comments. We really value the input from the reviewer and thank them for this.

Reviewer overview: This paper describe a new simple parametrization included in the JULES land surface model to take into account for specific behaviour of crops into the model. This follow a general and important recent trend in global land surface models to better represent the behaviour of ecosystem largely managed that greatly differ from natural vegetation. I think that it is an important and necessary effort for land surface model and then I greatly support such kind of development in the JULES model. Moreover this kind of paper perfectly fit with the scope of geoscientific model development. So I recommend the publication of the paper. However I think that it can

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be improved in several ways. This is the reason why I quoted "major revision", even if it doesn't mean a lot of additional efforts.

RC: As general comment, I find the paper clear and the equation well described even if the style of the paper is sometime a little surprising. In particular, it asks some questions to the reader like "how much detail is required ?" "what's more ?" etc.. which is not very conventional !

AC: The text has been modified to remove these questions.

New Text: 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:

RC: My main concern is that the model evaluation part is a little light and should be enhanced. For instance, the model is only evaluated on 3 sites for a total of four sites/years. Then only soy bean and maize is represented. A large set of sites on crops are now available with some sites that have more than 10 years of data. This allows to cover the main crops types and several regions in the world. So it is really a pity that the model be compared to a so limited set of data. I think that evaluation should be really improved by comparing with a larger dataset that allows evaluation of the 4 crops types represented, for different regions and considering longer time period to evaluate the ability of the model to represent the interannual variability for each site. Only H and LE are compared. Why did you not include the NEE fluxes that are probably available for these sites ? (or at least an estimation of the GPP as if I understand well, there is only a short model

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spinup that does not allow to equilibrate the soil carbon).

AC: We are limited to sites that have the appropriate forcing data for JULES as well as useful evaluation data. We have included more sites to the evaluation of Soybean and Maize but were unable to include sites for Wheat or Rice. We have also included plots of GPP and yield for the sites where these data were available. The emphasis of this paper was on the global runs as including crops as a component of our earth system model was the motivation for the model development. As such we focused the analysis of inter-annual variability on the global runs. The site evaluations were included to demonstrate the flexible nature of the model. However, we have added more years to the site evaluation so readers can see how the model performed.

New Text: Figures added - see attached. These new figures are discussed in the results and discussion sections. Figures ?? and ?? compares JULES-crop simulations for the soybean crop type with standard JULES  $C_3$  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  $C_3$  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 for  $C_3$  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 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 observa-

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tions. 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 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. 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 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 results also show that JULES (crop and standard configurations) is not able to capture the magnitude of observed GPP fluxes. This suggests that using the standard physiological parameters for  $C_3$  and  $C_4$  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.

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RC: In the simulation at global scale only maps from model results and comparison to averaged global yields is shown. A more regional view of ability of model to reproduced spatial distribution of yields is missing. Obviously, as mentioned by the authors direct comparison the actual yields is difficult since the model does not take into account for specific local management an species. But at least in would be important to see if model is able to reproduce regional climate driven difference in estimated yield.

AC: Regional variations in yield are due to a combination of climate and management. Because we do not include spatial variations in management (which was beyond scope of the initial model development) a better evaluation would be comparing simulated and observed year to year variability for key countries. As such we have included country level time series of yield for each crop type.

New Text: Figures added. These new figures are discussed in the results and discussion sections.

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

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each grid cell by the observed harvested area from ? regrid 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  $\text{kg m}^{-2}$  to  $\text{Mg ha}^{-1}$ . 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  $t_{soil,2} < T_{bse}$ . A similar analysis was conducted to determine country level yields with averages taken over all gridcells within a particular country.

The average simulated yield for maize is over-estimated however, the model does a reasonable job of reproducing the inter-annual variability at the global ( $r = 0.48$ ) and country scale (Fig. ?? a). For soybean, 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 ( $r = 0.39$ ) 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 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.

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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 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.

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,

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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.

RC: Likewise several model configurations have been implemented but are not evaluated in the paper. For instance a method to automatically determine the sowing date has been implemented but no results are shown in the paper. A method to take into account for photoperiod constraint on estimation of the development index was also included but not used in the simulations. I think it would be important to add a part showing the impact of these different parametrisations on simulated fluxes and yields.

AC: The “dynamic sowing” option is one that we feel needs more testing and as such results have not been included in this paper. However, we wish to inform users of this functionality and so describe it in the paper. We have added a sentence to explain why results from this option are not included. The photoperiod sensitivity was not included because it made determining TTveg, TTrep almost impossible. This is because we would then have three variables that needed calibrating at each grid cell (total TT, critical photoperiod, and sensitivity to photoperiod) from one observation (growing season duration). There are other options for determining TTveg and TTrep and so we included it as an option for future users if their studies required it.

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New text: 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.

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 photoperiod, and sensitivity to photoperiod) from one observation (growing season duration).

Specific comments:

RC:p 6780: Even if the different model parameters are defined in table 1, it would be more convenient for the reader to remind it after equation, this is for instance the case for  $TT_{emr}$ ,  $TT_{veg}$  and  $TT_{rep}$  in equation 3

AC: Description added New text: 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

RC:p 6780 eq 4: what is the meaning of the 0.012 term ?

AC: The factor 0.012 is a unit conversion ( $\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  to  $\text{kg C m}^{-2} \text{ s}^{-1}$ )

RC:p 6781: there is a paragraph that justify definition of continuous coefficients for allocation to biomass compartments that is very long and not very clear. I think this could be shortened as it is obvious for me that defining a parametrisation for allocation coefficient is ever better than a lookup table !

AC: This paragraph has been simplified. See above

RC:p 6783 eq 9,11,13: I didn't find the definition of  $f_c$  ?

AC: The description is in Table 1.

RC:p 6785 l 19: Typo, Missing the T of "The"

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AC:Amended

RC:p 6790 : I am surprised in figure 8 to see so little differences in simulated LE flux for instance considering the large difference in LAI between the standard and crop version. In particular there is a large LE pic in May simulated all the versions even if LAI is very low in the crop version. Do you have an explanation for that ? I think it would be important to discuss this point as it is mentioned that at the end, the new parametrization does not change a lot the result, which is indeed what we see in the site simulation but that is strange for me as LE should be, in spring and summer, largely driven by plant transpiration and then by LAI. So I would expect that the large LAI change induced by the new crop parametrization should have a larger impact on fluxes.

AC:We were surprised by this also. It could be due to a weak relationship between LAI and evaporation in JULES (Lawrence and Slingo, 2004). We added some discussion of this to the text.

New Text: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.

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.

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Interactive comment on Geosci. Model Dev. Discuss., 7, 6773, 2014.

**GMDD**

7, C3251–C3268, 2015

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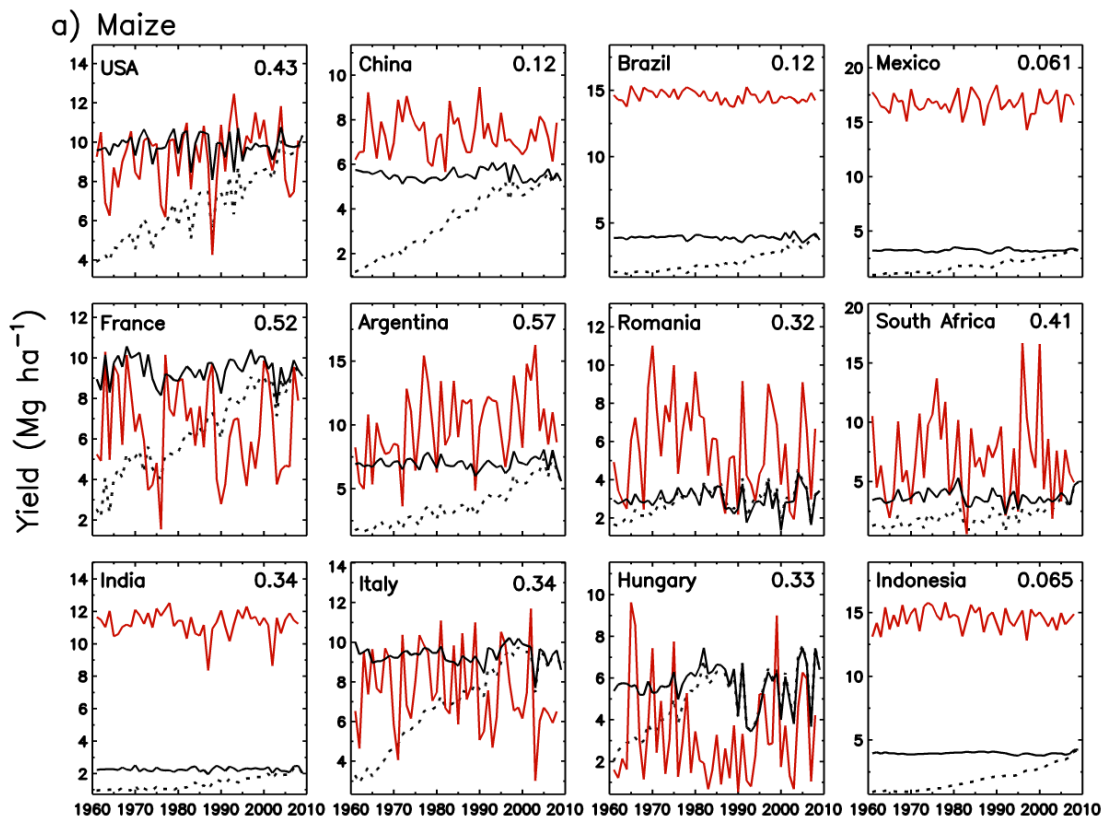
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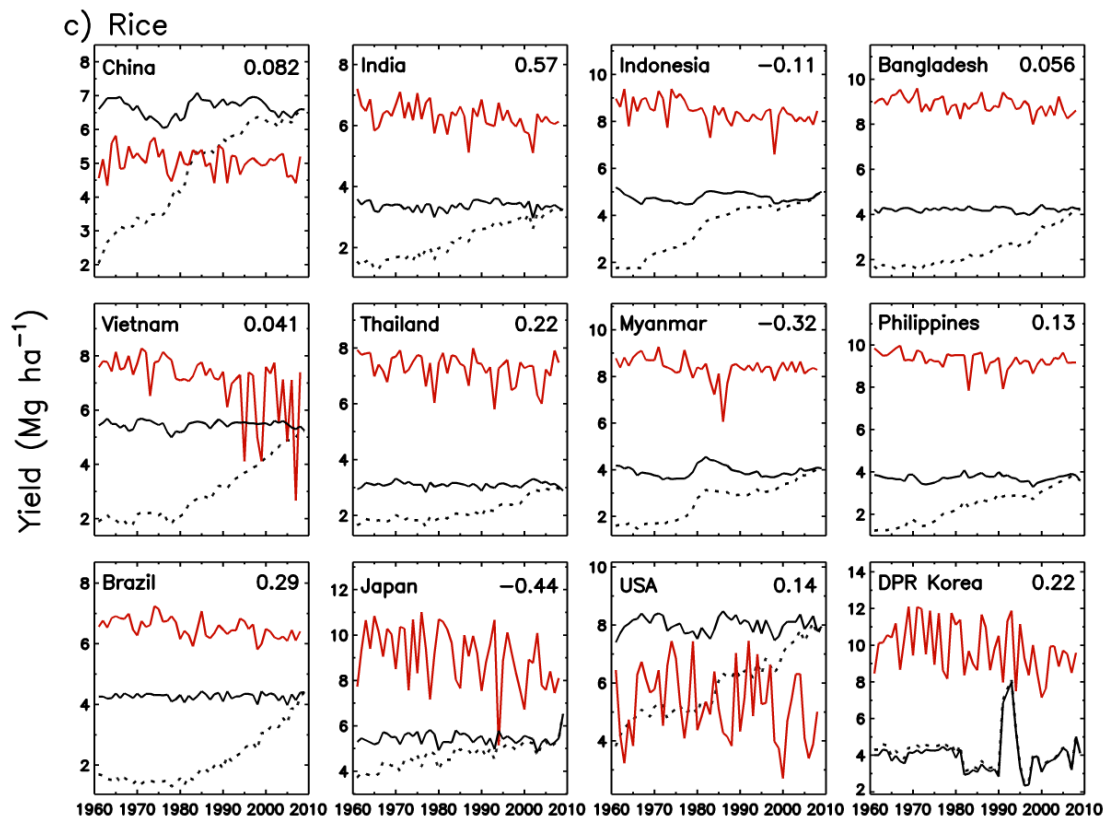
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**Fig. 1.** Simulated (red), observed (black dashed) and de-trended observed (black) country level yields of a) Maize between 1961–2008. Value

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**Fig. 2.** Simulated (red), observed (black dashed) and de-trended observed (black) country level yields of c) Rice between 1961–2008. Values in the top right are results of a

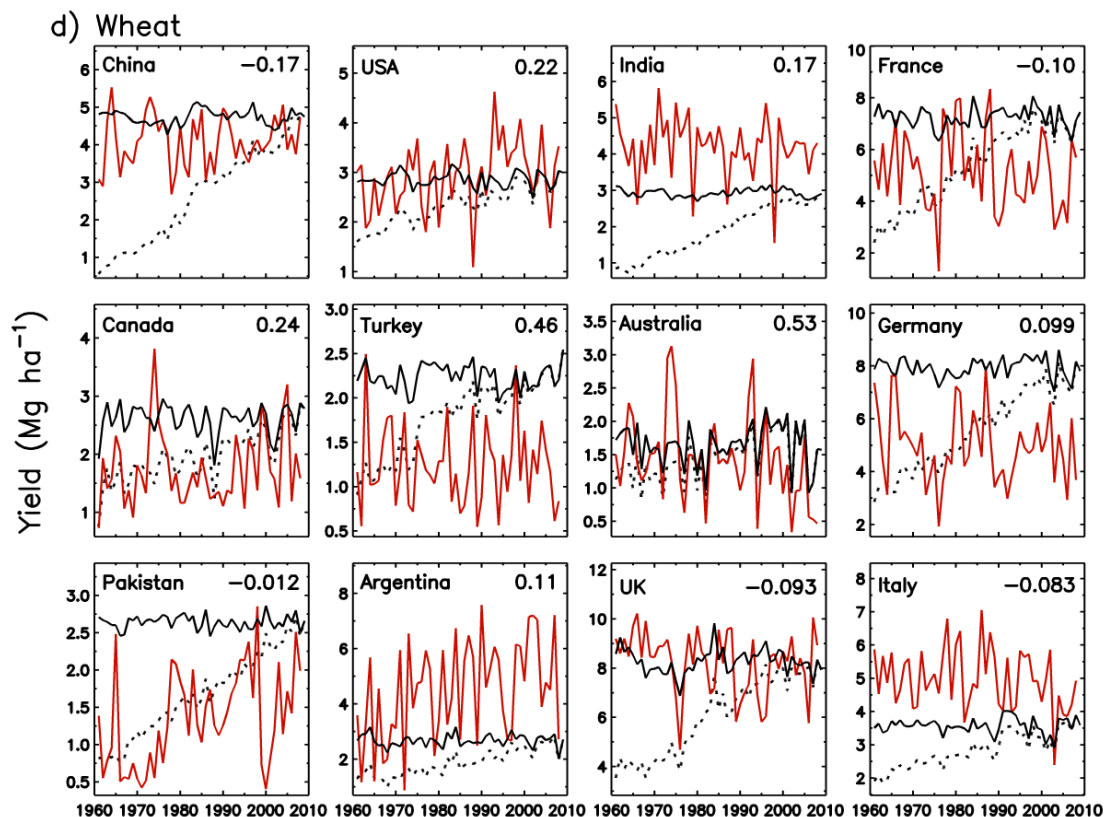
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**Fig. 3.** Simulated (red), observed (black dashed) and de-trended observed (black) country level yields of d) Wheat between 1961-2008. Values in the top right are results of a

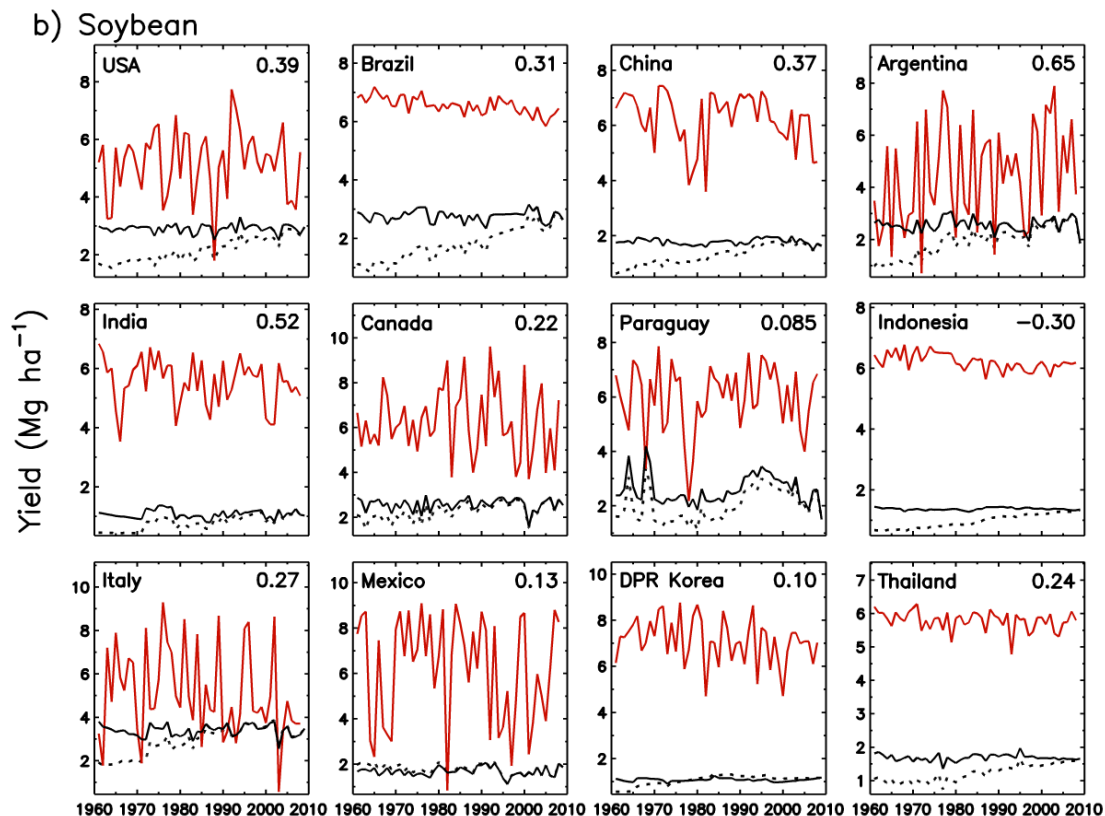
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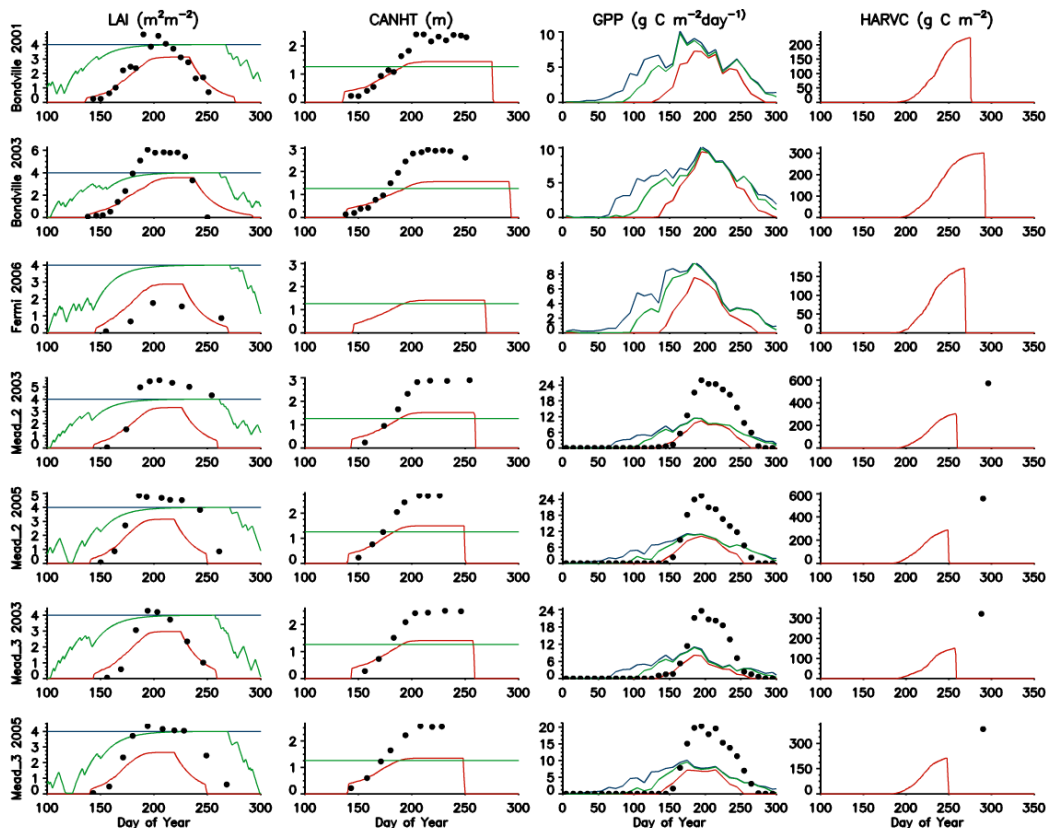
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**Fig. 4.** Simulated (red), observed (black dashed) and de-trended observed (black) country level yields of b) Soybean between 1961-2008. Values in the top right are results of a

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**Fig. 5.** 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.

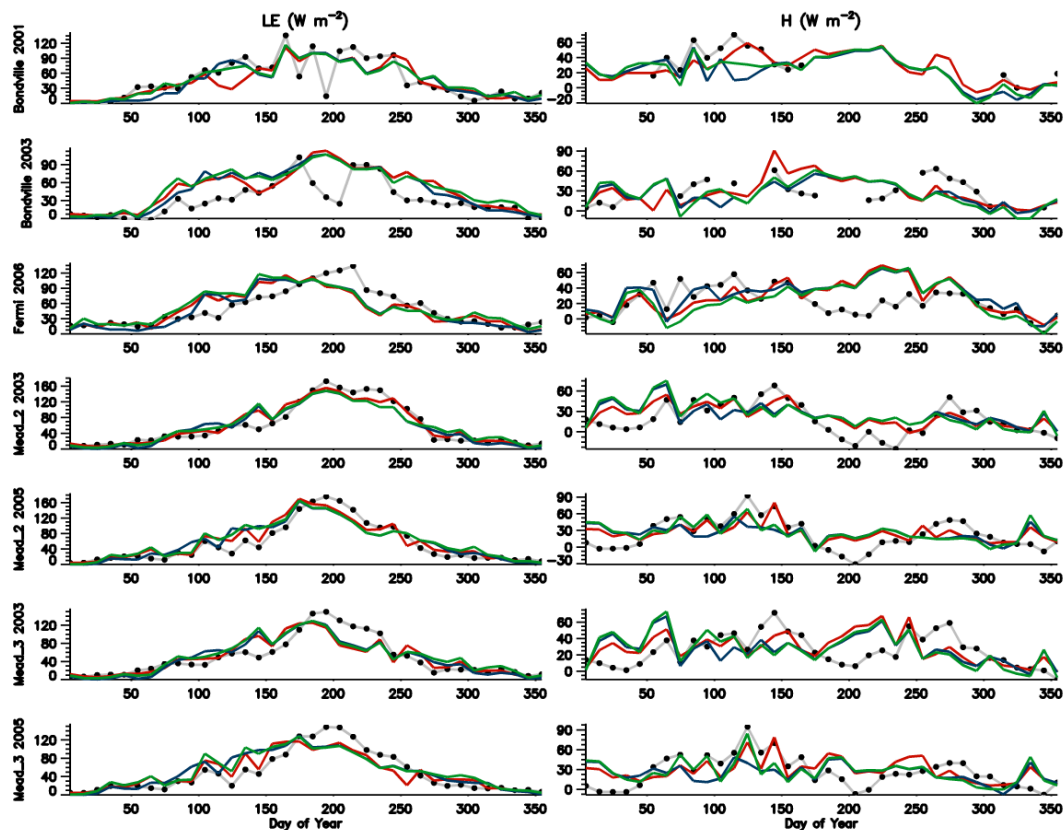
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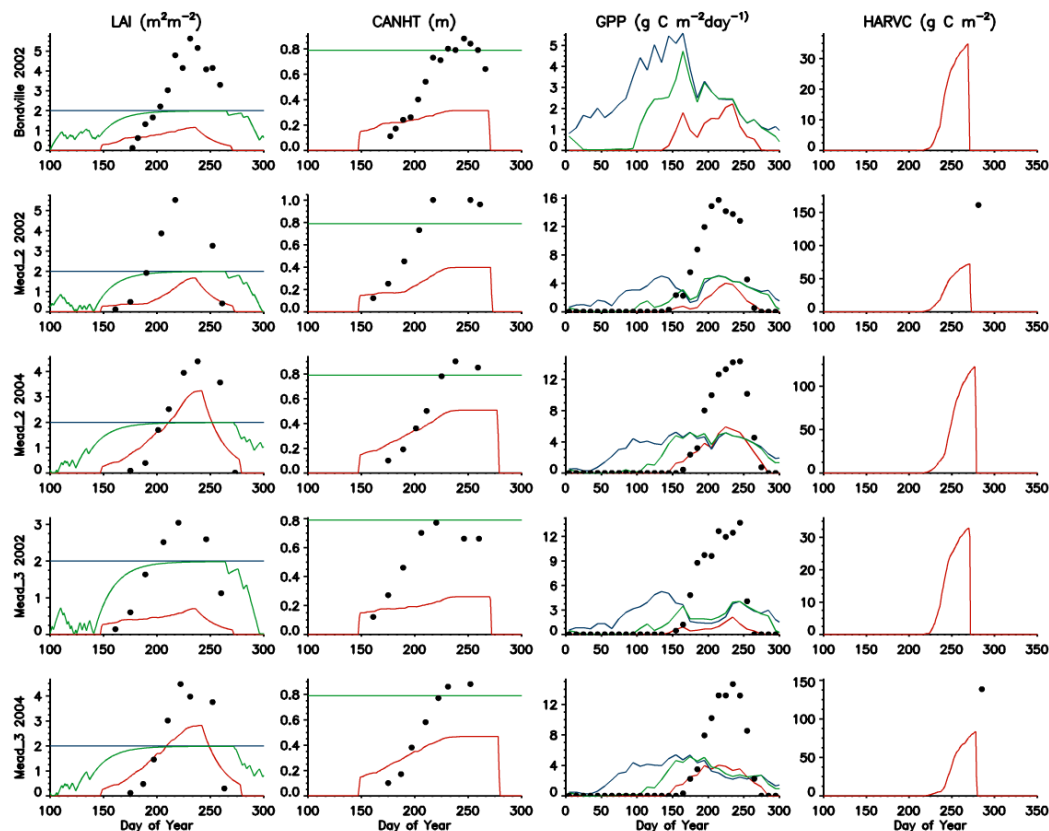




**Fig. 6.** Simulated (solid lines) and observed (dots) Latent (LE) and Sensible (H) heat fluxes at a range of fluxnet sites and years.

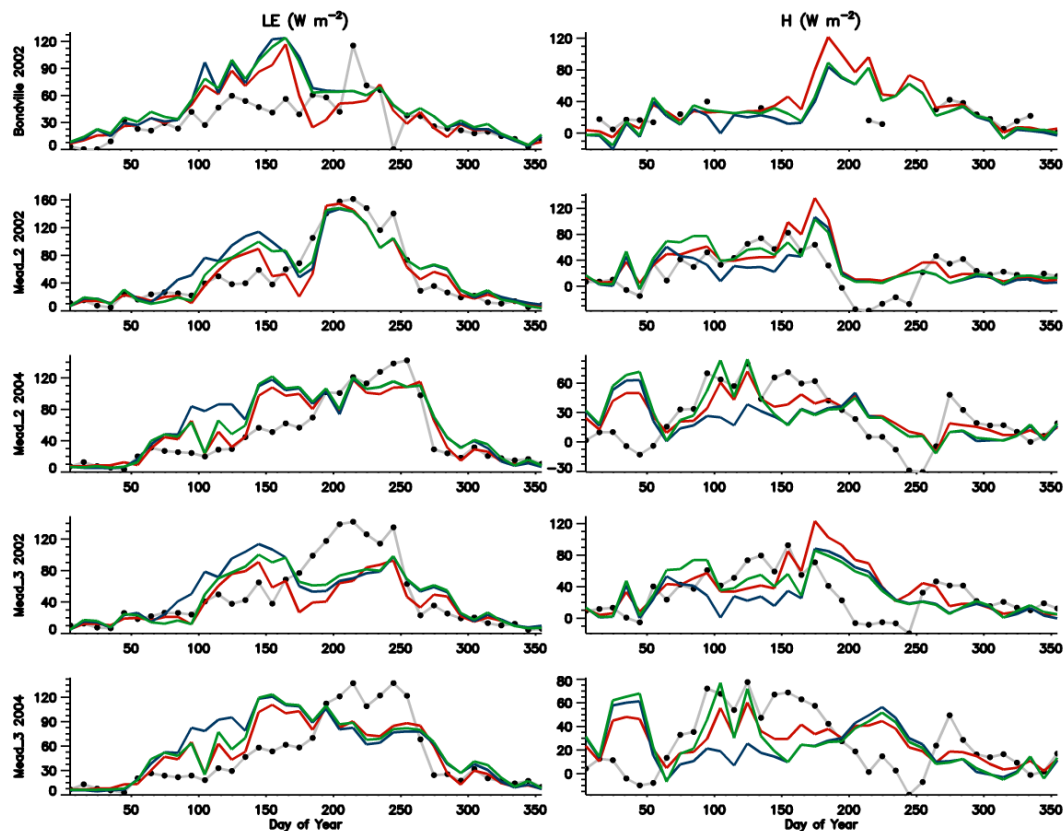
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**Fig. 7.** Simulated (solid lines) and observed (dots) Leaf Area Index (LAI), Canopy Height (CANHT), Gross Primary Production (GPP) and Harvest Carbon (HARVC) at a range of fluxnet sites and years

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**Fig. 8.** Simulated (solid lines) and observed (dots) Latent (LE) and Sensible (H) heat fluxes at a range of fluxnet sites and years.

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## ***Interactive comment on “JULES-crop: a parametrisation of crops in the Joint UK Land Environment Simulator” by T. Osborne et al.***

**T. Osborne et al.**

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Received and published: 5 February 2015

AC: This is a reponse to reviewer's comments. We really value the input from the reviewer and thank them for this.

Reviewer Overview: The manuscript by Osborne et al. describes the JULES-crop model, an extension of the JULES land surface model to improve the representation of crops in there. The main focus of the manuscript is on global-scale application of the model (although the possibility for parameterisation at the local scale is discussed), and the model is evaluated against global yield data and site observations.

The manuscript is well-written and clear, and the strong focus on description of the model formulation and model structure is suited for Geoscientific Model Development.

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However, the manuscript needs a crucial improvement in two major aspects before it can be considered for publication:

RC: (1) In general, the model is described well, but the origin of some important equations and their parametrisation is lacking (e.g., Eqs. 1, 2, 8, 10, 11). As these equations are crop-specific for most part, I presume that these are not based on the original JULES model, and the sources that these equations originate from (or were inspired by) should be provided. (If they originate from JULES, please state this explicitly.) Similarly, the origin of parametrisations could be documented better. Even when "tuned" (p. 6785, l. 6), there must be some understanding of the range of these parameters based on the literature.

AC: The origins of the equations have now been added to the text.

RC: (2) The evaluation of the model and discussion of its performance are very superficially, and do not add much information (or confidence) in their current form. Global simulations are performed, highlighting the discrepancy between potential yields as simulated by the model and actual yields as observed (yield gap), but the authors do not discuss whether the difference is realistic. There are estimates of the yield gap (e.g., Licker et al., 2010), which the model could be compared to at the global scale - there should be at least an attempt to a better comparison with the observations.

AC: While the 'yield gap' estimates provide useful information it is not possible for us to directly compare model results. In the paper by Licker et al (2010), the climatic yield potential (which is used to generate the yield gap) is based on the 90th centile of current yields (under current management practices) within a climatic zone (as defined by GDD and soil moisture). What we model is crop yield in response to climate only – not including management practices but with a globally constant parametrization of nutrient availability (in reality a description of top level leaf nitrogen which scales GPP). Therefore, JULES-crop can simulate negative biases (due to a lack of irrigation for example) and positive biases (due to pests, disease, lower nutrient availability). That

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being said we can use the Licker et al data to qualitatively compare our results i.e. is JULES-crop over-predicting in regions with a high yield gap. We have added some discussion about this to the paper and changed the global yield figure to include observations. We have also expanded the analysis of inter-annual variability (looking more regionally) which we believe is a better evaluation of JULES-crop given the difficulties of reproducing spatial patterns due to varying management practices.

New text: 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 (Thornton et al, 2009). JULES-crop will still exclude many management factors which affect regional yields. Licker et al (2010) 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 (Sacks et al, 2009)).

RC:Similarly, the site simulations (performed for a few crops and locations only) focus exclusively on the impact of the seasonally changing LAI on the energy balance, and ignore the model's performance in terms of crop growth characteristics (are yield, crop height, net carbon fluxes, seasonality, etc. simulated correctly?).

AC:We do include evaluation of crop height and LAI but have also added GPP and

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## GMDD

7, C3269–C3281, 2015

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yield to the figures.

New text: Figures added

RC:The discussion of the model's abilities and shortcomings should be extended. E.g., the manuscript mentions the fact that spring wheat is not representative for large wheat-growing regions, but fails to discuss the implication of this for e.g. surface properties or surface fluxes. Similarly, the yield gap is acknowledged, but there is no discussion on the impact of this on the model's performance as a land surface scheme in a global model. What does this imply for the feedbacks to the climate system? I would recommend the authors to improve the manuscript in these two aspects to make this an attractive article for publication.

AC: We have expanded the discussion section to consider the yield gap as suggested-see above. We have also highlighted the implications of not including winter wheat.

New text: 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).

RC:Major comments: Fig. 1: The figure seems to suggest that there is no accounting for belowground carbon pools in the model. Is this correct?

AC:Yes, JULES-crop is not coupled to soil carbon model yet.

RC:6781/6782: I am somewhat confused by the authors' estimate of the number of parameters needed to describe the allocation (not least by the statement " $2+(4-1)=6$ ", p.

AC:This should be  $2*(4-1)$ . This paragraph has been simplified.

New Text: 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

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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.

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:

RC:6781, l. 19). I understand that there is no allocation to harvested compounds during the vegetative period (p. 6782, l. 12), but this would result in  $(3-1)+(4-1)=5$  parameters, whereas the authors consistently talk about 6. Moreover, the parameter  $\tau$  in Eq. 5 is not mentioned or described in further detail, whereas it will need an estimate (constant or temporally varying), adding to the parameters needed for the allocation description. Clarification would be appreciated.

AC:We talk about 6 as the equations apply over the whole growing season (DVI= 0-2). The parameter in Eq 5 is described on line 8. Its value varies by crop, but is constant in time and space.

RC:6783, l. 16: Are the parameters  $k$  and  $\lambda$  fitted for each crop separately, or do you derive a relationship valid for all crops? And how applicable is the relationship to the crops that are not grown at the FLUXNET site? Do you anticipate this relationship to be applicable at a global scale?

AC:Yes they are specified for each crop. Variations in height are a function of variations in the amount of carbon partitioned to stems, rather than in the relationship between stem carbon and height. By specifying crop-specific parameters we capture the fact that given the same stem carbon, maize is taller than soybean. There may be small differences in this relationship for different varieties of maize (for example) but these differences are not the primary reason for variations in height and stem thickness.

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RC:6788, l. 14: I do not agree with the statement that early season performance is crucial for future growth: Yes, there is a strong feedback from early assimilation and leaf growth to light interception, but this feedback decreases rapidly upon closure of the crop canopy.

AC: Agreed - text removed.

RC:Minor comments and technical corrections:

RC:6778, l. 9: replace "know" by "known"

AC:Done

RC:6779, l. 1: please refer to Table 1 for explanation of the subscripts b, o and m

AC:Done

RC:6780, l. 15: add "with" (or equivalent) before "the following equation" AC:Done

RC:6781, l. 18: I take that " $2+(4-1)$ " should read " $2*(4-1)$ " AC:Done

RC:6784, l. 7: remove "being" AC:Done

RC:6784, l. 15: The mentioning of five plant functional types is somewhat confusing, as you talk about 9 surface types before. Upon rereading, I realized that 4 out of 9 are not plant-covered, which may explain the difference. Please clarify this.

AC:Text modified to clarify that there are 9 surface types including 5 plant functional types. New text: 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,  $C_3$  grass,  $C_4$  grass, shrubs, bare-soil, inland lakes, snow and ice.

RC:6784, l. 18 (and elsewhere): please use subscripts for  $C_3$  and  $C_4$ . AC:Done

RC:6784, l. 20: The mentioning of tropical oilseed confused me - do you consider this to be a cereal crop? What is the difference between crops and crop types in this

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sentence?

AC:The values of the parameters required in Eqs. (1)–(13) determine which crop type is being simulated. (e.g. maize, wheat, or rice). It is also possible that alternative sets of parameter values could be specified to simulate different cultivars of the same crop or generic crop functional types. Text has been amended to clarify this.

New text: 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.  $C_3$  cereals) or cultivar (e.g. Soy bean PS123121 or Soy bean 21h321).

RC:6785, l. 3: I presume that the comma is placed wrongly here and should go after "model" instead? AC:Done

RC:6785: "widely used in the literature": Why not add references for these?

AC:Reference added New Text: 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 ?).

RC:6785, l. 19: replace "he" with "The" AC:Done

RC:6785, l. 21: Please specify the rough dimensions of an N96 grid for readers that are not familiar with climate modelling. AC:Done

RC:6785, L. 27: add "was" before "obtained" AC:Done

RC:6786, l. 3: What do these ratios between length of vegetative and reproductive period originate from?

AC:They are an approximation of the relative length of each phase.

RC:6786, l. 15: replace "an" with "at" AC:Done

RC:6788, l. 8: replace "over estimated" with "overestimated" AC:Done

RC:6788. l. 28: replace "where as" with "whereas" AC:Done

C3275

GMDD

7, C3269–C3281, 2015

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RC:6790, l. 17: replace "over estimates" with "overestimates" AC:Done

RC:6790, l. 21: replace "over estimate" with "overestimate" AC:Done

RC:6791, l. 16: The feedbacks mentioned here are typically referred to as biogeophysical, not biogeochemical. AC:Done

RC:6791, l. 17: replace "parametrization" with "parametrisation" AC:Done

RC:6792, l. 20: replace "day length" by "daylength" AC:Done

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Interactive comment on Geosci. Model Dev. Discuss., 7, 6773, 2014.

**GMDD**

7, C3269–C3281, 2015

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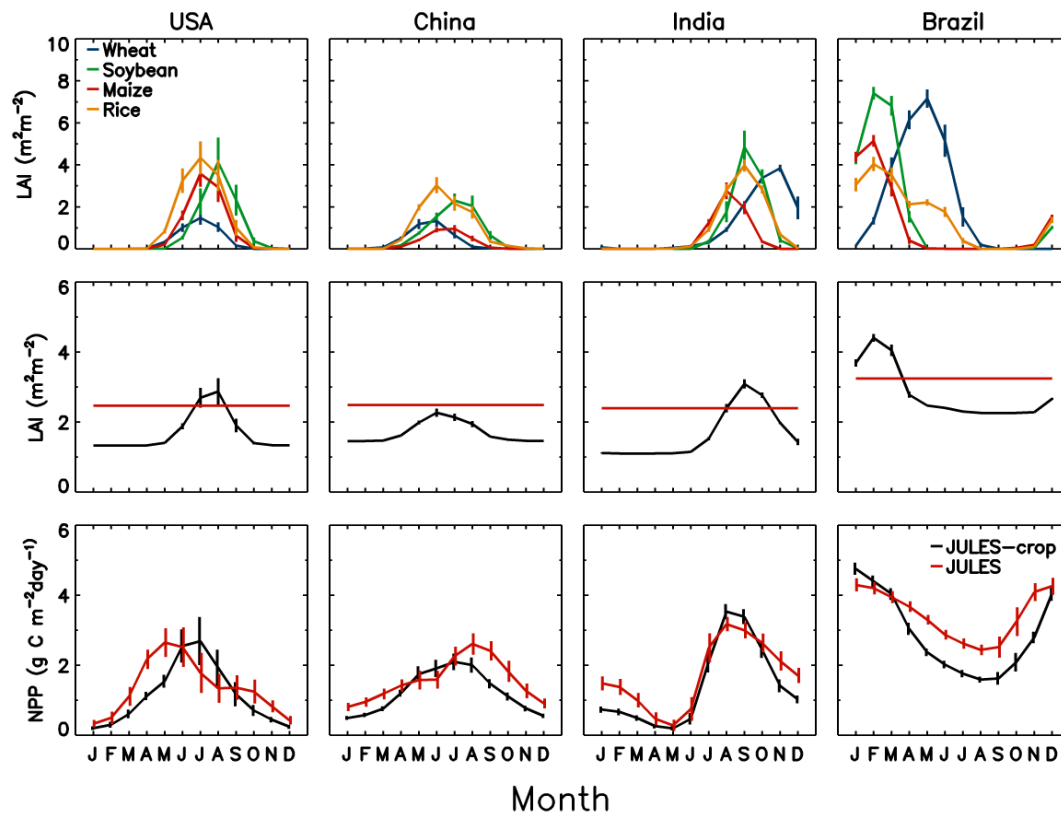
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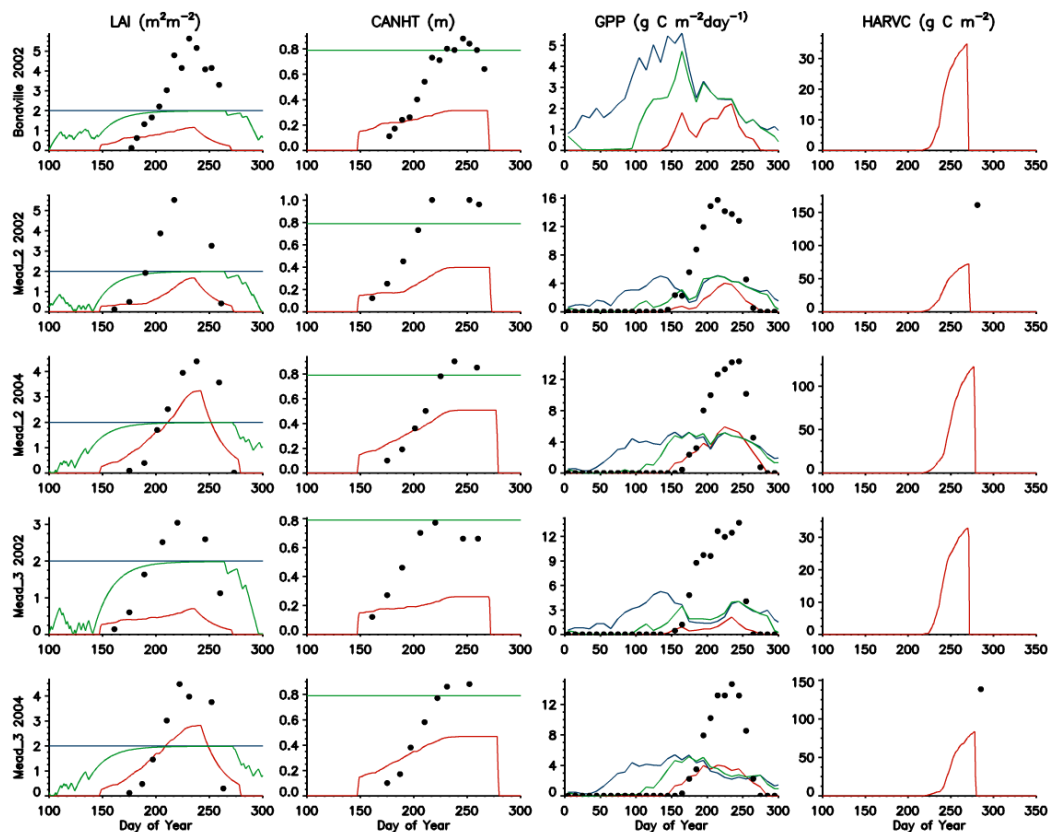
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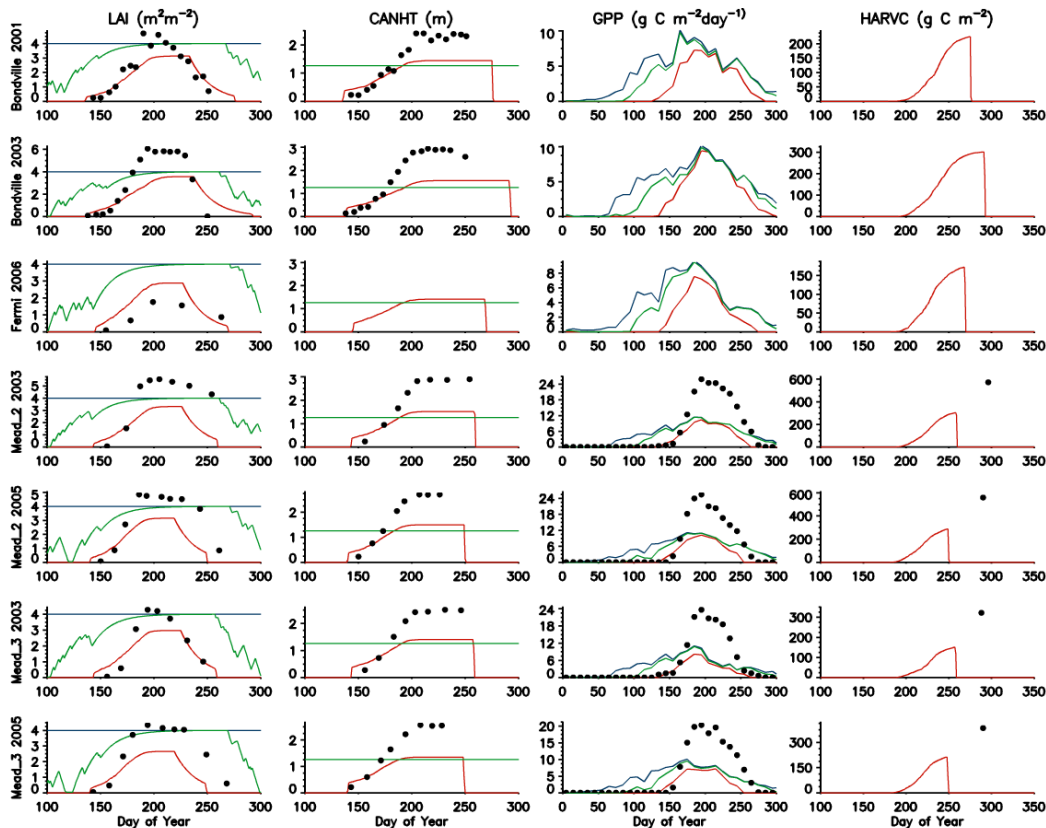
**Fig. 1.** Country crop area weighted annual cycle of crop type (top) and grid-box mean (middle) leaf area index (\$LAI\$) and grid-box mean (bottom) Net Primary Production (NPP).

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**Fig. 2.** 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.

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**Fig. 3.** 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.

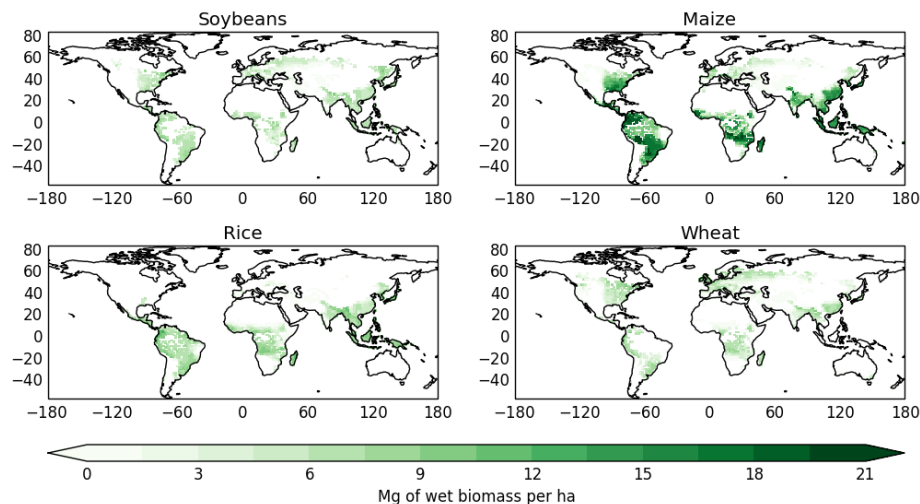
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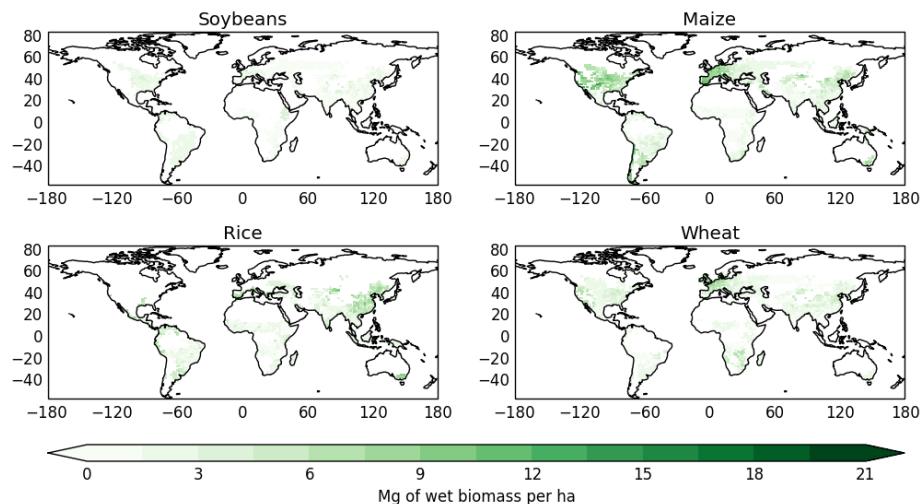
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**Fig. 4.** Global yields simulated by JULES-crop (Mg per ha)

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**Fig. 5.** Global yield observations (Mg per ha)

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# **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, ~~soy-bean~~soybean, maize and rice ~~is presented~~. JULES-crop demonstrates skill in simulating the inter-annual variations of yield for maize and ~~soy-bean~~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~~. However, more effort is needed to develop the parameterisation of the model for specific applications. Key future model developments identified include the ~~specification of the yield gap to~~ 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 ef-

fects of how changes in atmospheric conditions can impact upon crop growth, development 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. Betts et al. (2013) 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 (van Ittersum et al., 2003). 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 (Deryng et al., 2011; Osborne et al., 2013), and inter-comparison of many crop models in simulating the same crop and the same set of conditions (Asseng et al., 2013).

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, McPherson et al. (2004) 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. McPherson et al. (2004) identify the differences in phenology between managed crop-lands and natural grasslands as the determinant of the differences.

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 Levis, 2010). Some developments have been motivated by improving the carbon and water budget of land surface modelling (Bondeau et al., 2007), others to include crop-lands in global or regional climate models to better represent their impact on the atmosphere (Lokupitiya et al., 2009; Chen and Xie, 2012; Levis et al., 2012), while others have been motivated to consistently simulate both yield and environmental impacts (Kucharik and Brye, 2003).

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 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 Best et al. (2011) and Clark et al. (2011). JULES does not currently include an explicit parametrisation of crops, instead over cropped regions the ~~C3 or C4~~ C<sub>3</sub> or C<sub>4</sub> grass plant functional type are used. Previous work has included crops in the model. Osborne et al. (2007) 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, Van den Hoof et al. (2011) extended JULES to include a

-parametrisation of wheat based on the crop model SUCROS. Neither Osborne et al. (2007) nor Van den Hoof et al. (2011) developed 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 parametrization of crops applicable to many crop types and at the global scale. However, the model has been designed to be flexible meaning users can re-parametrize the model depending on requirements (e.g. to represent different crop cultivars).

The following Section describes the model development, Sects. -3 and 4 present evaluation of the new model when applied at global and site levels, respectively, followed by a -Discussion (Sect. -5).

## 2 Model description

The essence of JULES-crop is illustrated in Fig. -1. 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 influenced by temperature. In addition to the new equations describing crop growth and development, 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 types requiring extra parameters to be specified. The detailed description of the crop parametrization 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 -1 and 2, respectively.

## 2.1 Growing season and development

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  $\theta_2$  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 ( $T_{\text{soil},3} > T_b + 2K$ , 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 ( $T_{\text{eff}}$ ) is calculated based upon the crop-specific cardinal temperatures ( $T_b, T_o, T_m$  - see Table 1 for description).

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

$T_{\text{eff}}$  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,  $T_{\text{eff}}$  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 (Challinor et al., 2004). 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 for short-day plants and negative for long-day plants. This conceptual approach was motivated by Loomis R.S. (1992). Therefore, to slow development  $T_{eff}$  is multiplied by the relative photoperiod effect (RPE), which is defined as follows:

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

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:

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

The growing season ends when  $DVI = 2$  at which time the prognostic variables related to crop growth ( $L, h, C_{root}, C_{harv}, C_{resv}$ ) 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  $DVI = 1$  or if  $LAI > 15$ . Vernalisation, a cold temperature requirement for development in some crops, is not included in this model version.

## 2.2 Growth

- 5 To simulate crop growth, Net Primary Productivity ( $\Pi$ ) is accumulated over a -day and then partitioned between five carbon pools: root ( $C_{\text{root}}$ ), structural stem ( $C_{\text{stem}}$ ), stem reserves ( $C_{\text{resv}}$ ), leaves ( $C_{\text{leaf}}$ ), and harvested organs ( $C_{\text{harv}}$ ). The original formulation for  $\Pi$  in JULES includes 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. ~~46~~ 42 of Clark et al., 2011) and
- 10 root carbon is set to equal leaf carbon. Because these carbon pools are now explicitly simulated,  $\Pi$  is recalculated for the crop types the with following equation based on an algebraic reduction of the set of equations used in JULES:

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

- 15 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  $R_{\text{dc}}$  is the rate of non-moisture stressed canopy dark respiration.  $C_{\text{leaf}}$ ,  $C_{\text{stem}}$  and  $C_{\text{root}}$  are the carbon content of leaf, stem and root, respectively.

The carbon in  $\Pi$  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.

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

where  $\tau$  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, van Ittersum et al., 2003). But how much detail is required to describe the evolution of partition coefficients through the growing crop's duration? Say, for example, that only 2 values are wanted (to define the partition coefficient during vegetative and reproductive periods), and that there are 4 carbon pools, then we would need  $2 + (4 - 1) = 6$  partition coefficients (partition coefficients are only needed for 3 of the 4 pools, as the fourth is defined as 1 minus the sum of the other 3). If more detail in the evolution of the partition coefficients is desired, then more values are required at finer temporal (or thermal temporal) resolution. This can lead to very many partition coefficients being defined and used. Instead, we

Here we define the partition coefficients as a function of thermal time. Thus, for only using 6 parameters defining this functional form, we can 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  $\alpha$  and  $\beta$  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 ~~with only values for vegetative and reproductive periods, as, obviously, harvested components cannot be added to before flowering!~~) 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. 2 overlaid with example observed partitioning fractions from de Vries et al. (1989).

Following the formulation of de Vries et al. (1989), 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:

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

Leaf senescence is treated simplistically by mobilising carbon from the leaf to the harvest pool at a rate of  $0.05 d^{-1}$  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

5 for partitioning to leaves to cease since for some crop types this does not happen. :

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

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:

$$10 \quad L = \frac{C_{\text{leaf}}}{f_C} \text{SLA} \quad (9)$$

where

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

15 The values of  $\gamma$  and  $\delta$  were determined by fitting the relationship to the paired values of DVI and SLA reported in de Vries et al. (1989).

The amount of carbon in the stem is related to the crop height by (Hunt, 1990) :

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

20 The values of  $\kappa$  and  $\lambda$  were determined by fitting the relationship to the paired values of  $h$  and  $C_{\text{stem}}$  at the Mead FLUXNET site (Verma et al., 2005).

Equations (9) and (11) 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 Arora and Boer (2003) which defines the fraction of roots at depth  $z$  as:

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

5 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  $r_{\text{dir}}$  is a crop-specific parameter.

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

## 2.3 Changes to JULES code structure

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-C3~~  
15 ~~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 types-at-a-varieties-at-a  
site or grid box in a single integration of JULES, in addition to the standard five plant functional  
20 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-C3~~  
and ~~C4~~ grass, depending on the crop photosynthetic capacity (see Table -3).

The values of the parameters required in Eqs. -1)-(13) determine which ~~crop-crops are being~~  
~~simulated and can be varied according to different user requirements e.g crop species~~ (e.g. maize  
25 or wheat), ~~generic~~ crop type (e.g. ~~C3-cerealsor-tropical-oilseedC3 cereals~~) or cultivar (e.g. Soy  
bean PS123121 or Soy bean 21h321)are-being-simulated. Each parameter is described in Table  
-1. Values for each parameter can 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~~model, simulations for the period 1960 to 2010 were performed over the global domain. Four crop types were simulated; wheat, ~~soy-beans~~soybean, maize and rice. Parameter values are in Table 4 and were either taken from the crop science literature or ~~tuned~~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  $\gamma$  and  $\delta$  were calibrated against data in de Vries et al. (1989). The allometric coefficients  $\kappa$  and  $\lambda$  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 ~~widely used in the literature~~in line with the range of values reported in the literature (see Porter and Gawith (1999) and Sanchez et al. (2014) ). The effect of photoperiod was not included (by setting  $P_{\text{crit}}$  to 24) due to our method of determining thermal time between emerging and flowering ( $\text{TT}_{\text{veg}}$ ~~and~~) and thermal time between flowering and harvest ( $\text{TT}_{\text{rep}}$ ) (see below).

The parameter  $r_{\text{dir}}$  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.

~~he~~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 ~~(Le Quéré et al., 2013)~~. This was regridded to a ~~n96~~ grid (1.875 degrees longitude x 1.25 degrees latitude) and used with ancillaries from HadGEM2-ES ~~(Collins et al., 2011; Jones et al., 2011)~~ 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

5 Sacks et al. (2010), and a  $\tau$ -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 Sacks et al. (2010) sowing date, the crop reached  $DVI = 2.0$  at the Sacks et al. (2010) harvesting dates, with  $x = TT_{veg} / (TT_{veg} + TT_{rep}) = 0.5, 0.45, 0.6, 0.6$  for ~~soy-beans~~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 photoperiod, and sensitivity to photoperiod) from one observation (growing season duration). For comparison a  $\tau$ -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 3 shows the planting date of Sacks et al. (2010) and the derived maps of  $TT_{veg}$  and  $TT_{rep}$ . Sacks et al. (2010) derived 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  $\tau$ -purpose in global modelling studies by providing an approximate start point for the growing season ~~an~~-at the right time of year. Our method of calculating the crop thermal time requirements produces considerable spatial variability which is determined in reality by variation in the choice of crop cultivar chosen.

25 Other global crop modelling studies have approached the issue of specifying these requirements at the global scale in different ways. Osborne et al. (2013) 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 Deryng et al. (2011) related thermal time requirements (calculated from Sacks et al. (2010) in a  $\tau$ -similar manner to this study) to the annual accumulated thermal time and then used that relationship to determine thermal time requirements under future 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  $\tau$ -vernalisation parametrization in the model only spring wheat was considered. The crop fractions were taken

from Monfreda et al. (2008) and re-gridded to the n96 HadGEM2-ES resolution. Monfreda et al. (2008) provide observations in the year 2000 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. 4 along side global gridded observations for circa 2000 (Monfreda et al., 2008). Fig. 4 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. Typically, the lowest yields are simulated in arid regions which is unsurprising given the lack of any irrigation in the current model. For wheat the highest yields are simulated in the mid-latitudes whilst for maize and rice the highest yields are simulated in the Tropics. 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 5 shows 5 and 6 show the simulated global and country level yield for wheat, soy beans soybean, maize and rice between 1960–2008 compared to the reported yields of FAO (2014). Simulated global yield was determined by multiplying the simulated annual maximum yield at each grid cell by the observed harvested area from Monfreda et al. (2008) regrided 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  $C_{\text{harv}}$  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  $\text{kg m}^{-2}$  to  $\text{Mg ha}^{-1}$ . 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

$LAI > 15$  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.

The average simulated yield level for maize is over-estimated however, the model does a reasonable job of reproducing the inter-annual variability at the global ( $r = 0.48$ ) and country scale (Fig. 6 a). For soybean, 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 ( $r = 0.39$ ) and India ( $r = 0.52$ ) JULES-crop is able to reasonably capture inter-annual variability of yields (Fig. 6 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. 6 c). The average simulated yield level for wheat is similar to the most recent observations but when comparing the year to year fluctuations in yield, the correlation between simulated and observed is low ( $r = 0.03$   ~~$r = 0.019$~~ ). 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 ( ~~$r = 0.56$~~   $r = 0.53$ ), in which spring wheat varieties dominate.

For soy bean, average yield is much greater than observed but year on year variability is correlated with observations ( $r = 0.39$ ) providing some confidence in the model's ability to simulate the observed response of soy bean yield to climate. The simulated variability is much greater than observed. Similarly for maize, variability is over-estimated but does vary in line with observations ( $r = 0.50$ ). For rice, yield levels are higher than reported, variability is overestimated and not correlated with observations ( $r = 0.16$ ). The 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 any certain processes in the model (particularly those to do with land management). For example not including a representation of irrigation in the model which may explain why the model predicts lower yields than observations as irrigation would act to reduce the extent of crop failure in drought years. It may also be a result of the source-driven nature of the model. By

relying on assimilated carbon to increase crop size leading to greater growth, slight deviations in early growth can have potentially large consequences for future growth. In contrast, sink-driven models increase crop size before determining biomass growth and are therefore less sensitive to sub-optimal environmental conditions during the start of the growing season. The model also does not include the impacts 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.

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. 7 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, where as 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. 7 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 8 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 ~~when the heat flux~~ 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 (Verma et al., 2005), 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~~ C<sub>3</sub> grass for soybean, C<sub>4</sub> 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

Figure ?? Figures 9 and 10 compares JULES-crop simulations for the ~~soy-bean~~ soybean crop type with standard JULES ~~C3-C<sub>3</sub>~~ grass plant functional type with and without phenology, and with observations where available, ~~in 2002 and 2004 at the Mead FLUXNET site~~. The crop parametrisation captures the evolution of leaf area index ~~and crop height with different success in each year~~. In 2004 JULES-crop simulates the observed peak LAI well whereas in 2002 the simulated LAI is lower than observed. In both years the crop height is lower than observed (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-C<sub>3</sub>~~ 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 for ~~C3-C<sub>3</sub>~~ grass of 2.0 all year. Interestingly, the more realistic simulation of vegetation cover does not lead to improved simulation of surface fluxes. In both years 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 10). Towards the start of the growing season the standard configuration of JULES with constant LAI = 2.0 ~~over-estimates-overestimates~~ latent heat flux due 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 Fig. ?? At Bondville in 2001 the crop simulation slightly underestimates the peak LAI observed leading to slightly lower latent heat flux than observed Figures 11 and 12. The crop 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 observed LAI, canopy height and latent and sensible heat fluxes although again there are no major improvements in model ~~performace~~ performance with the explicit inclusion of crops. At

Fermi in 2006 the crop specific simulation captures the observed evolution of LAI reasonably well with ~~excessive-peak~~ LAI slightly closer to observations than the standard JULES simulations. ~~This-However, this~~ again does not improve the simulation of heat fluxes.

10 All model configurations overestimate the partitioning of energy in to latent heat before the growing season begins and underestimate it during the crop growing season, despite widely varying LAI values. This ~~comparison-therefore-could be due to the relatively weak LAI-surface conductance relationship found in JULES (Lawrence and Slingo, 2004)~~. This is reflected in the low sensitivity to LAI between fixed and grass phenology. In these simulations we would  
15 ~~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-does-model may~~ not guarantee improved performance in the model in other aspects. ~~However, it is also worth~~ The results also show that JULES (crop and standard configurations) is not able to capture the magnitude of observed GPP fluxes. This suggests that using the standard physiological  
20 parameters for C<sub>3</sub> and C<sub>4</sub> 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 ~~may-not-be-optimal~~ are probably not optimal for site simulations.

## 25 5 Discussion and Conclusions

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 ~~biogeochemical-biogeophysical~~ feedbacks to climate including albedo,  
5 partitioning of turbulent fluxes and seasonality of LAI. In this paper we present results from a -generic, crop functional type ~~parametrization-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.

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 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.

As a 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 (Thornton et al., 2009). JULES-crop will still exclude many management factors which affect regional yields. Licker et al. (2010) 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 (Sacks et al., 2009) ).

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 overestimates the magnitude of this variability. ~~The global runs show that the model under-predicts yield in arid regions which highlights the importance of including irrigation in the near future.~~ 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.

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 (Lawrence and Slingo, 2004) 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 ~~day-length~~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).

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

Parameter	Unit	Equation	Description
$T_b$	°C	Eq.-(1)	Base temperature
$T_o$	°C	Eq.-(1)	Optimum temperature
$T_m$	°C	Eq.-(1)	Maximum temperature
$TT_{emr}$	°C d	Eq.-(3)	Thermal time between sowing and emergence
$TT_{veg}$	°C d	Eq.-(3)	Thermal time between emergence and flowering
$TT_{rep}$	°C d	Eq.-(3)	Thermal time between flowering and maturity/harvest
$P_{crit}$	h	Eq.-(2)	Critical photoperiod
$P_{sens}$	$h^{-1}$	Eq.-(2)	Sensitivity of development rate to photoperiod
$r_{dir}$	–	Eq.-(13)	Coefficient determine relative growth of roots vertically and horizontally
$\alpha_{root}$	–	Eq.-(6)	Coefficient for determining partitioning
$\alpha_{stem}$	–	Eq.-(6)	As above
$\alpha_{leaf}$	–	Eq.-(6)	As above
$\beta_{root}$	–	Eq.-(6)	As above
$\beta_{stem}$	–	Eq.-(6)	As above
$\beta_{leaf}$	–	Eq.-(6)	As above
$\gamma$	$m^2 kg^{-1}$	Eq.-(10)	Coefficient for determining specific leaf area
$\delta$	–	Eq.-(10)	As above
$\tau$	–	Eq.-(5)	Fraction of stem growth partitioned to $C_{resv}$
$f_C$	–	Eqs.-(9), (11), (13)	Carbon fraction of dry matter
$\kappa$	–	Eq.-(11)	Allometric coefficient which relates $C_{stem}$ to $h$
$\lambda$	–	Eq.-(11)	As above

**Table 2.** Crop model variables in JULES-crop.

Variable	Unit	Equation	Description
New variables			
$T_{\text{eff}}$	$^{\circ}\text{C}$	Eqs. (1), (3)	Effective temperature
DVI	–	Eqs. (3), (6), (8), (10)	Development Index
$C_{\text{leaf}}$	$\text{kg } \text{C m}^{-2}$	Eqs. (4), (5), (8), (9)	Leaf carbon pool
$C_{\text{stem}}$	$\text{kg } \text{C m}^{-2}$	Eqs. (4), (5), (11)	Stem carbon pool
$C_{\text{root}}$	$\text{kg } \text{C m}^{-2}$	Eqs. (4), (5), (13)	Root carbon pool
$C_{\text{harv}}$	$\text{kg } \text{C m}^{-2}$	Eqs. (5), (7), (8)	Harvested organ carbon pool
$C_{\text{resv}}$	$\text{kg } \text{C m}^{-2}$	Eqs. (5), (7)	Stem reserve carbon pool
$p_{\text{leaf}}$	–	Eqs. (5), (6)	Fraction of NPP partitioned to $C_{\text{leaf}}$
$p_{\text{stem}}$	–	Eqs. (5), (6), (7)	Fraction of NPP partitioned to $C_{\text{stem}}$
$p_{\text{root}}$	–	Eqs. (5), (6)	Fraction of NPP partitioned to $C_{\text{root}}$
$p_{\text{harv}}$	–	Eqs. (5), (6)	Fraction of NPP partitioned to $C_{\text{harv}}$
$P$	h	Eq. (2)	Photoperiod (day length)
RPE	–	Eqs. (2), (3)	Relative Photoperiod Effect
Existing variables			
$T$	$^{\circ}\text{C}$	Eq. (1)	1.5 m temperature on each tile
$L$	$\text{m}^2 \text{ m}^{-1}$	Eq. (9)	Leaf area index
SLA	$\text{m}^2 \text{ kg}^{-1}$	Eqs. (9), (10)	Specific Leaf Area
$h$	m	Eq. (11)	Canopy Height
$\Pi$	$\text{kg } \text{C m}^{-2}$	Eqs. (4), (5)	Net primary productivity
$A_c$	$\text{kg } \text{C m}^{-2}$	Eq. (4)	Net carbon assimilation
$R_{\text{dc}}$	$\text{kg } \text{C m}^{-2}$	Eq. (4)	Canopy dark respiration

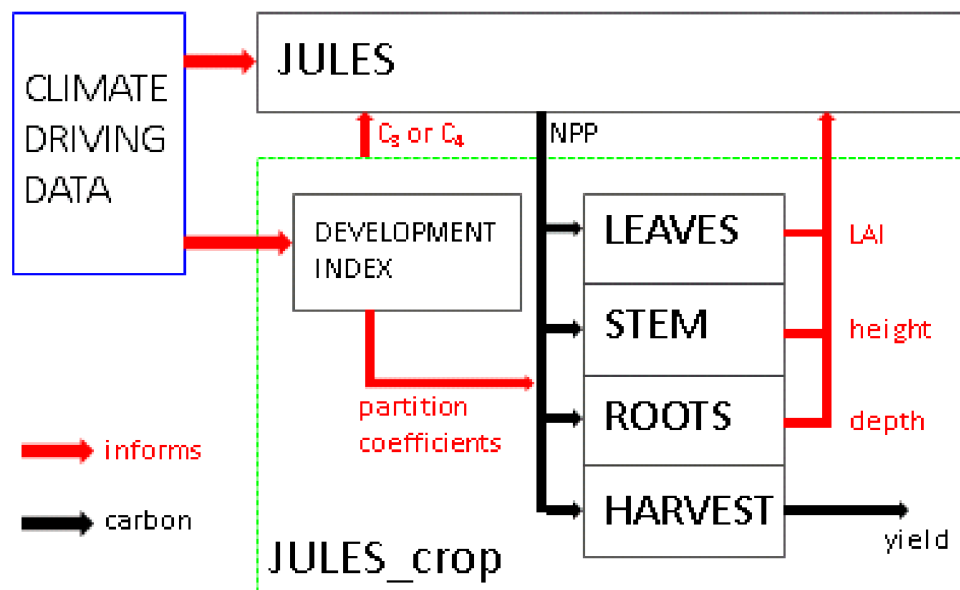
**Table 3.** JULES plant functional type parameters extended to represent crop types wheat, ~~soy~~  
~~bean~~soybean, maize and rice.

Crop type	Wheat	Soybean	Maize	Rice
$c3$	1	1	0	1
$d_r$	0.5	0.5	0.5	0.5
$dq_{\text{crit}}$	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
$n_{\text{eff}}$	$8.00 \times 10^{-4}$	$8.00 \times 10^{-4}$	$4.00 \times 10^{-4}$	$8.00 \times 10^{-4}$
$n_l(0)$	0.073	0.073	0.06	0.073
$\sigma_l$	0.032	0.032	0.025	0.032
$T_{\text{low}}$	0	0	13	0
$T_{\text{upp}}$	36	36	45	36

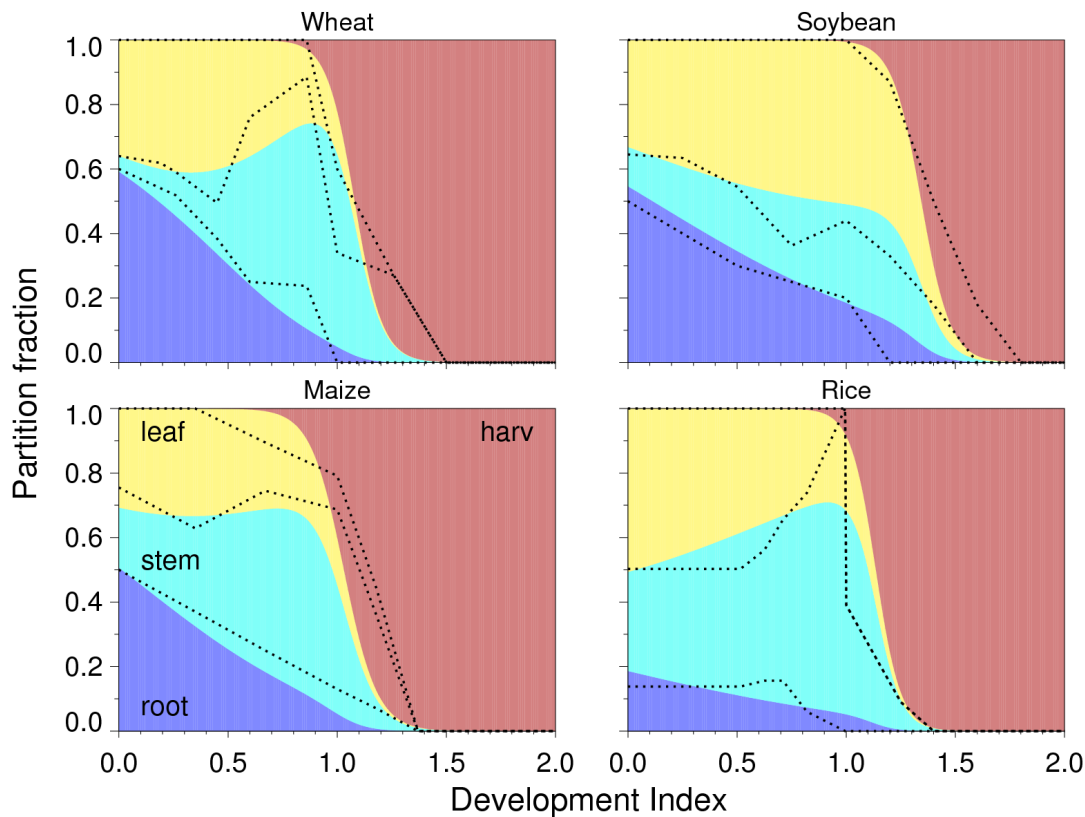
**Table 4.** Parameter values used to represent crop types wheat, ~~soy-bean~~soybean, maize and rice. See Table-1 for parameter definitions.

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.3		
$TT_{rep}$		See Fig.3		
$P_{crit}$	24	24	24	24
$P_{sens}$	0.00	0.00	0.00	0.00
$r_{dir}$	0.0	0.0	0.0	0.0
$\alpha_{root}$	18.5	20.0	13.5	18.5
$\alpha_{stem}$	16.0	18.5	12.5	19.0
$\alpha_{leaf}$	18.0	19.5	13.0	19.5
$\beta_{root}$	-20.0	-16.5	-15.5	-19.0
$\beta_{stem}$	-15.0	-14.5	-12.5	-17.0
$\beta_{leaf}$	-18.5	-15.0	-14.0	-18.5
$\gamma$	27.3	25.9	22.5	20.9
$\delta$	-0.0507	-0.1451	-0.2587	-0.2724
$\tau$	0.40	0.18	0.35	0.25
$f_C$	0.5	0.5	0.5	0.5
$\kappa$	1.4	1.6	3.5	1.4
$\lambda$	0.4	0.4	0.4	0.4

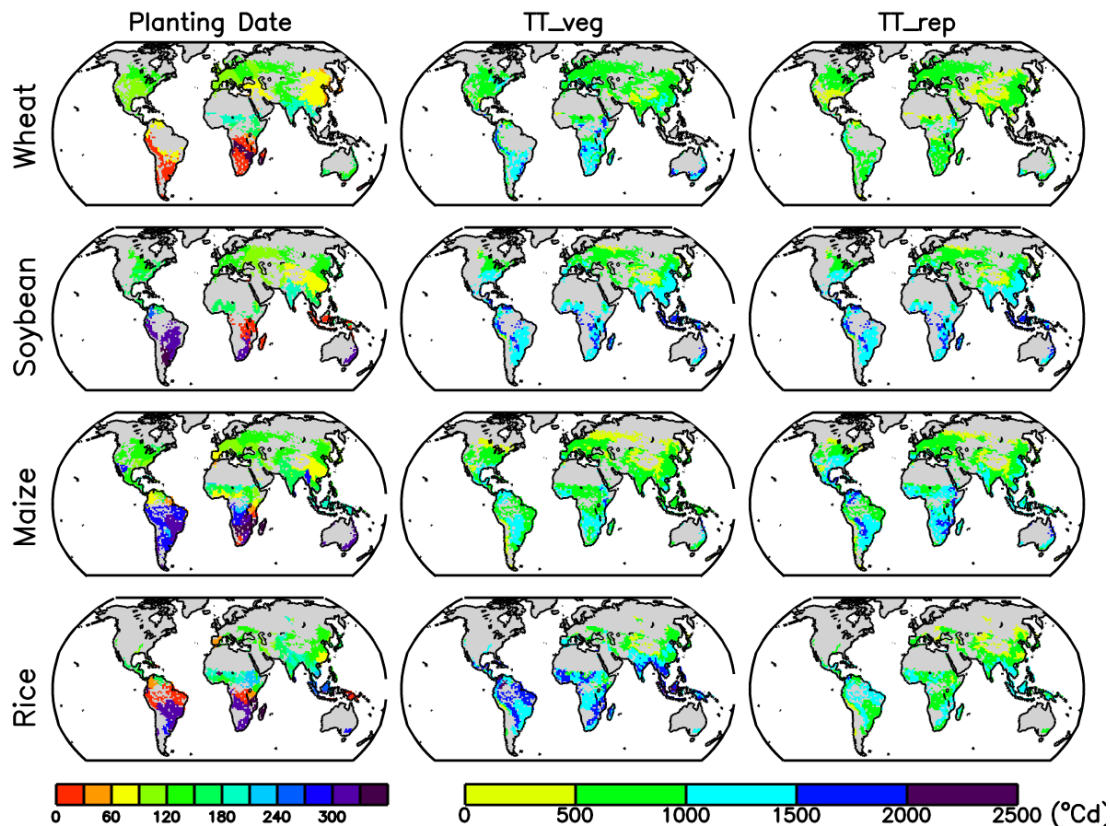




**Figure 1.** Schematic of JULES-crop.



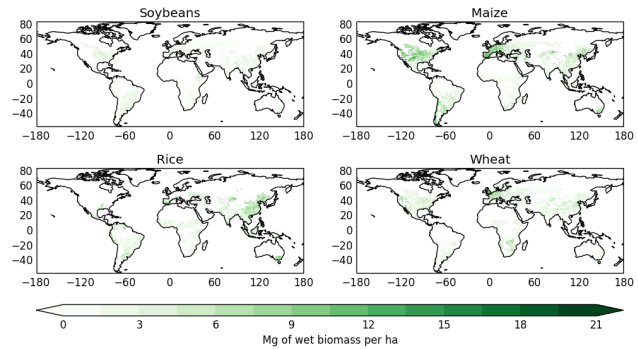
**Figure 2.** Fraction of daily accumulated net primary productivity partitioned to roots (purple), stems (blue), leaves (yellow) and harvested parts (red) of the crop as a function of development index (DVI; 0 = emergence, 1 = flowering, 2 = maturity) for wheat, rice, soybean and maize.



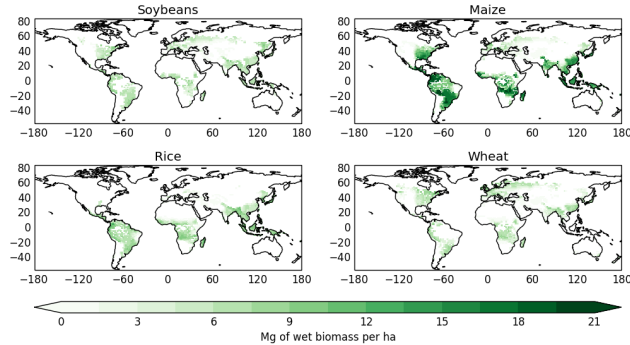
**Figure 3.** Global distribution planting date from Sacks et al. (2010), interpolated to NCEP grid, and the thermal time from emergence to flowering (TT<sub>veg</sub>) and from flowering to harvest (TT<sub>rep</sub>) for each crop type. See text for details of calculation.

Global distribution of average wheat, soy bean, maize and rice yield assuming a moisture content of

16 and a carbon fraction of 0.5.

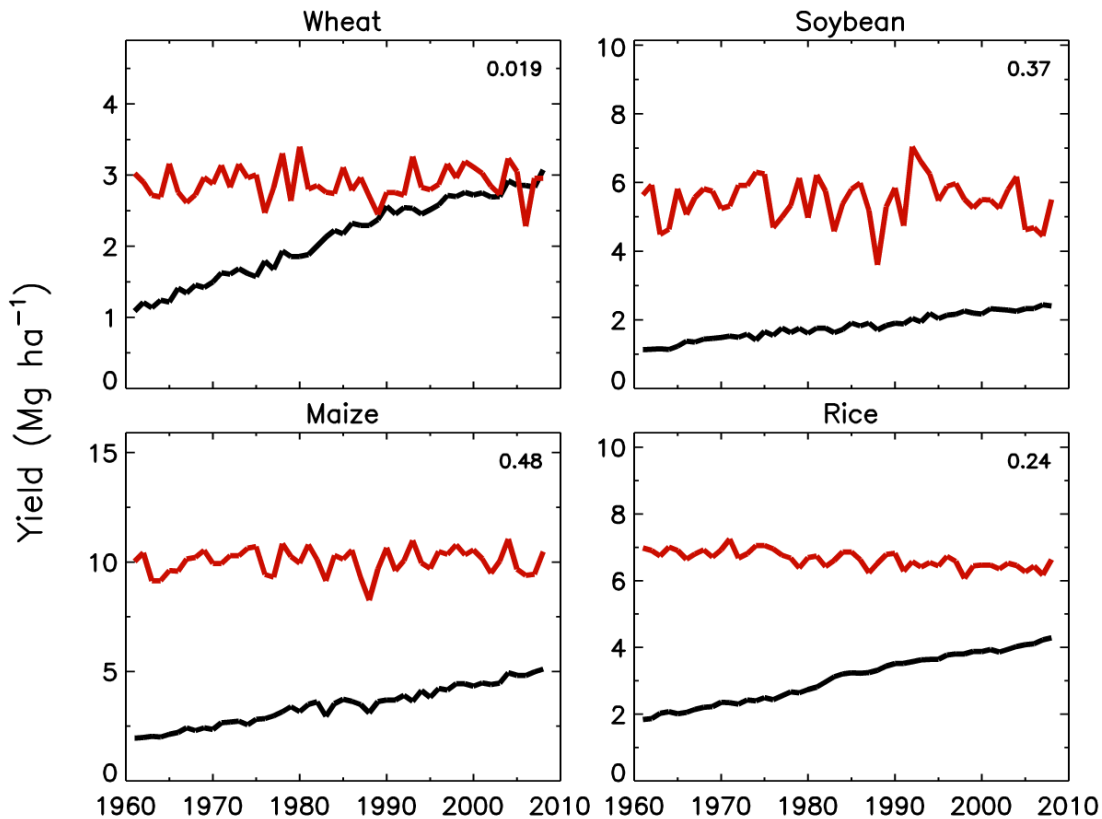


(a) Observations

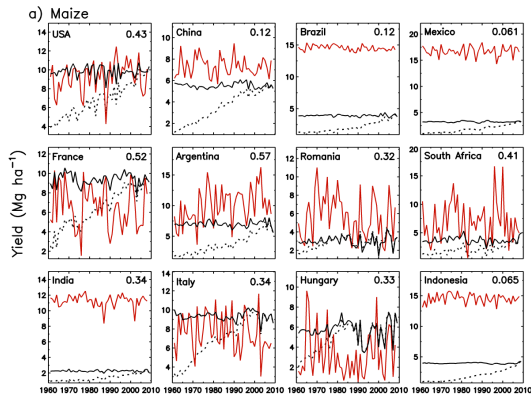


(b) JULES-crop

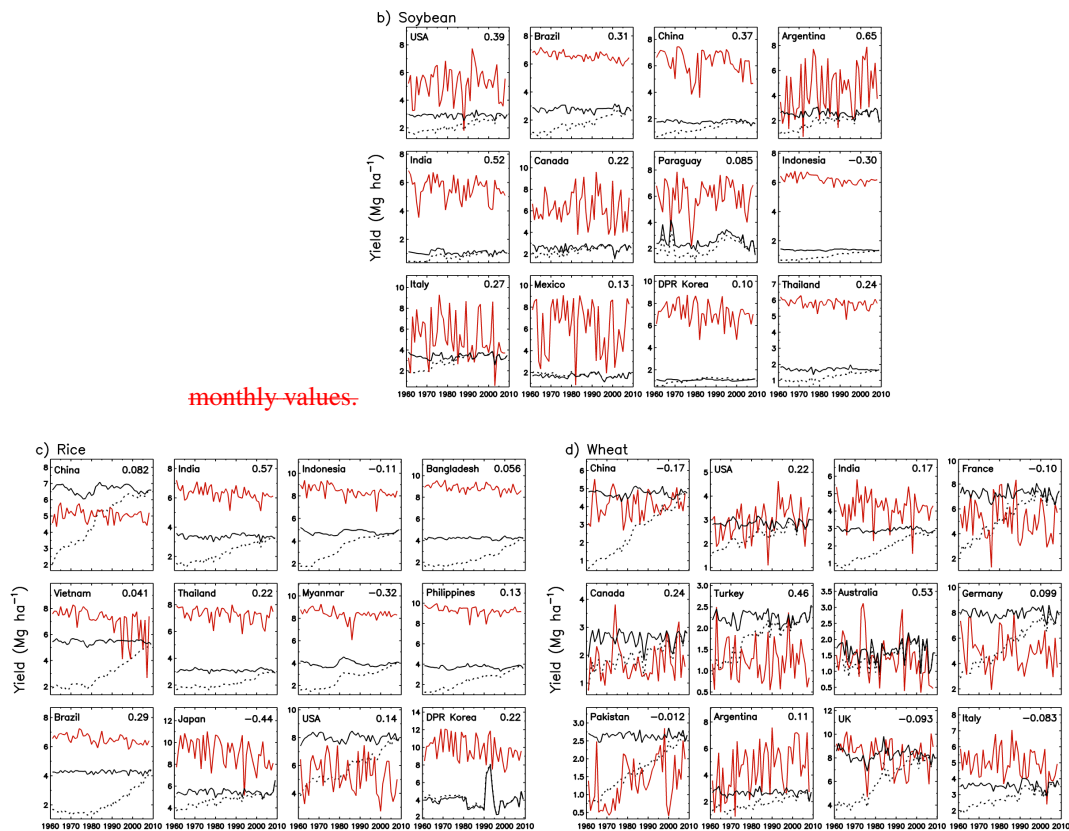
**Figure 4.** Global distribution of average wheat, soybean, maize and rice yield (Mg per ha) in a) observations (Monfreda et al., 2008) regridded to n96 resolution and b) JULES-crop global simulations (assuming a moisture content of 16% and a carbon fraction of 0.5)



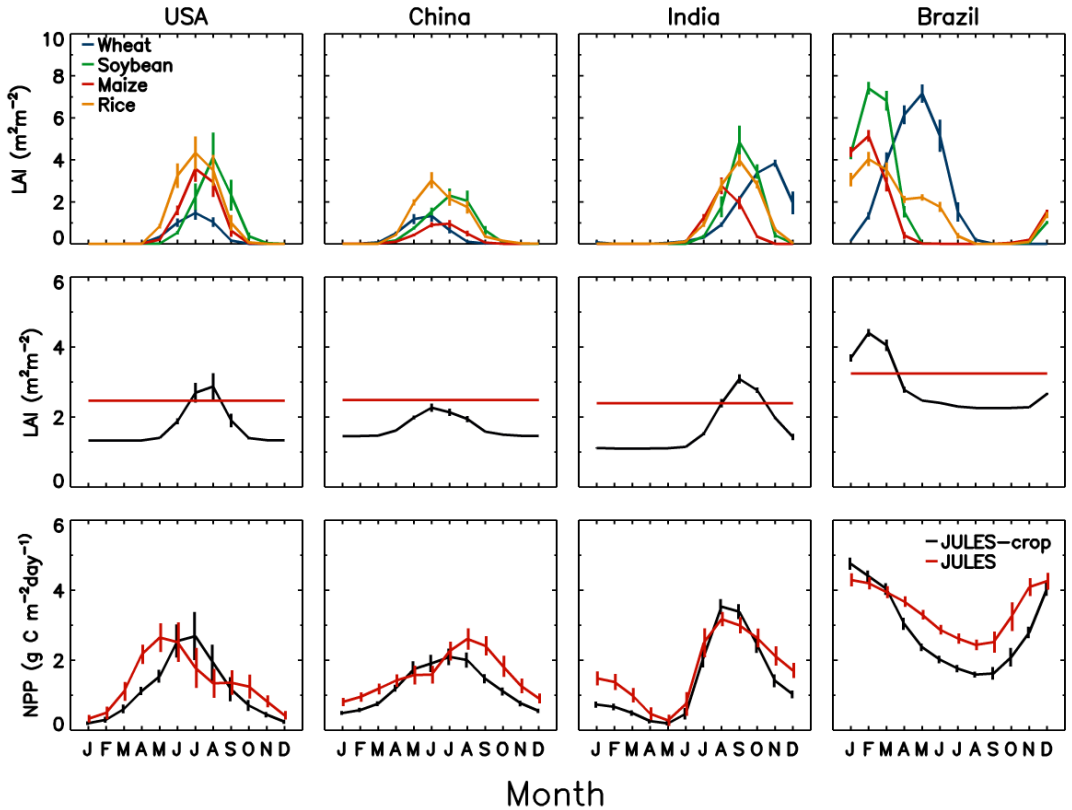
**Figure 5.** Simulated (red) and observed (black) global yield of wheat, ~~soy-beans~~soybean, maize and rice between 1961–20081961–2008. Values in the top right are results of a correlation between observations and JULES-crop simulations



Country-crop area-weighted annual-cycle of crop type (top) and grid-box mean (bottom) leaf area index (LAI). Area averages weighted by crop area in top panels, and total plant functional type area in bottom panels. Vertical bars indicate standard deviation of

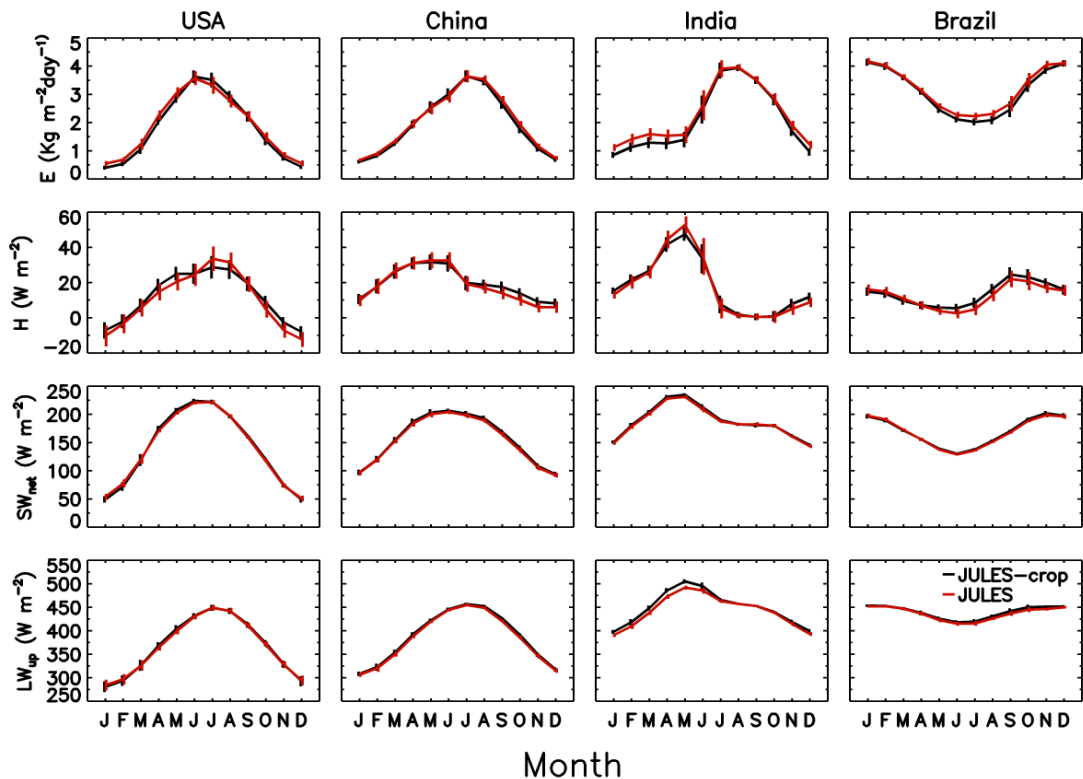


**Figure 6.** Simulated (red), observed (black dashed) and de-trended observed (black) country level yields of a) Maize, b) Soybean, c) Rice and d) Wheat between 1961–2008. Values in the top right are results of a correlation between de-trended observations and JULES-crop simulations



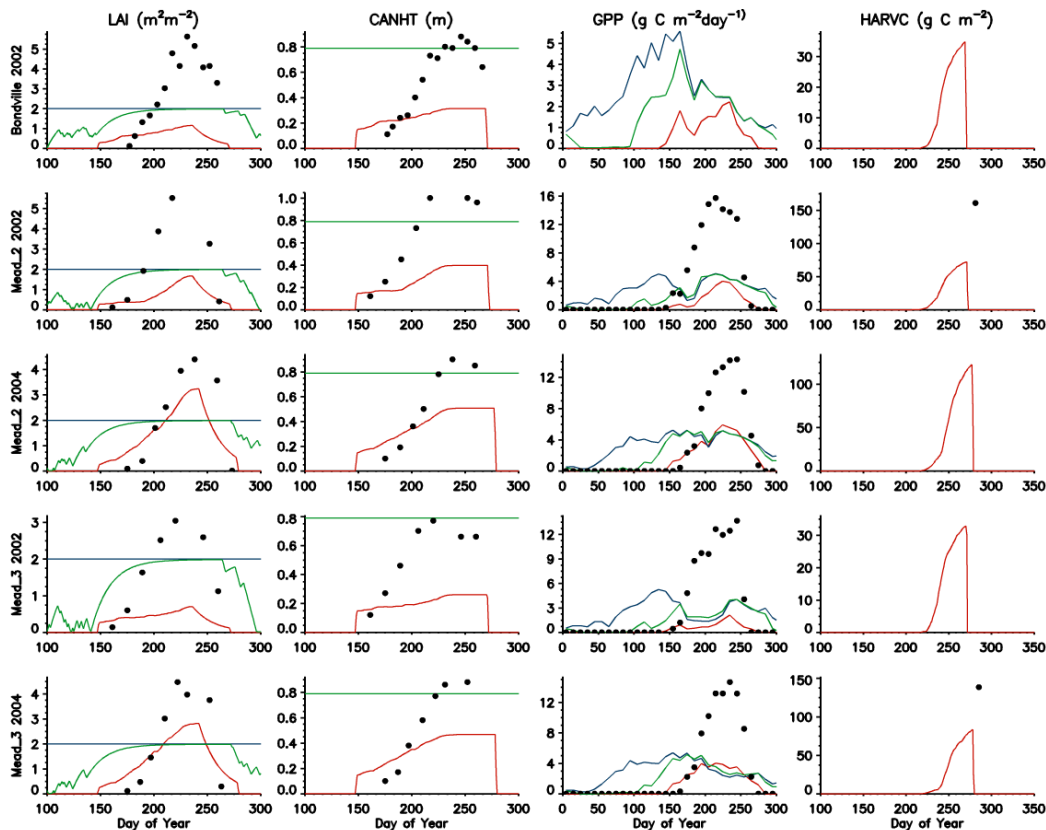
**Figure 7.** Country crop area weighted ~~average mean annual cycle of surface moisture flux crop type~~ ( $E_{top}$ ), ~~sensible heat flux and grid-box mean~~ ( $H_{middle}$ ), ~~net short-wave radiation leaf area index~~ ( $SW_{net}$ ,  $LAI$ ) and ~~upward long-wave radiation grid-box mean~~ ( $LW_{up}$ , bottom) from JULES-crop simulation Net Primary Production (red NPP). Area averages weighted by crop area in top panel, and standard JULES simulation (black) forced with CRU-NCEP meteorological driving data total plant functional type area in middle and bottom panels. Vertical bars indicate standard deviation of monthly values.





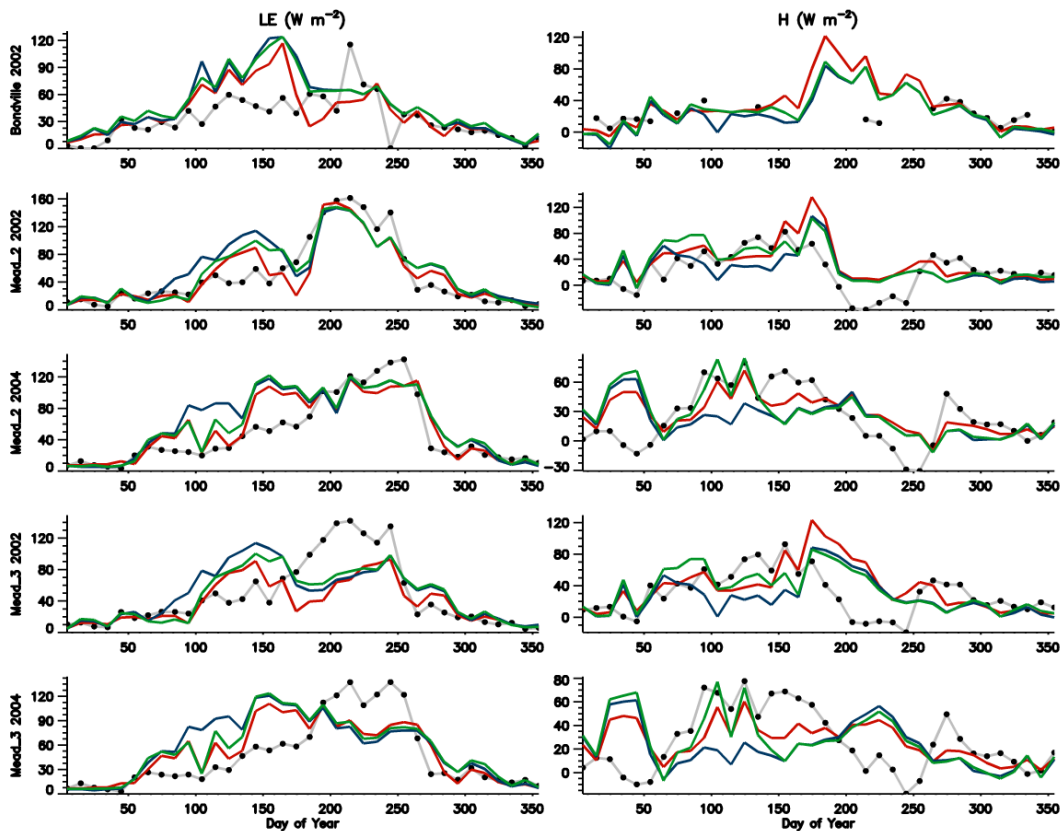
**Figure 8.** Country crop area weighted average mean annual cycle of surface moisture flux ( $E$ ), sensible heat flux ( $H$ ), net short wave radiation ( $SW_{net}$ ) and upward long wave radiation ( $LW_{up}$ ) from JULES-crop simulation (red) and standard JULES simulation (black) forced with CRU-NCEP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

# Soybean



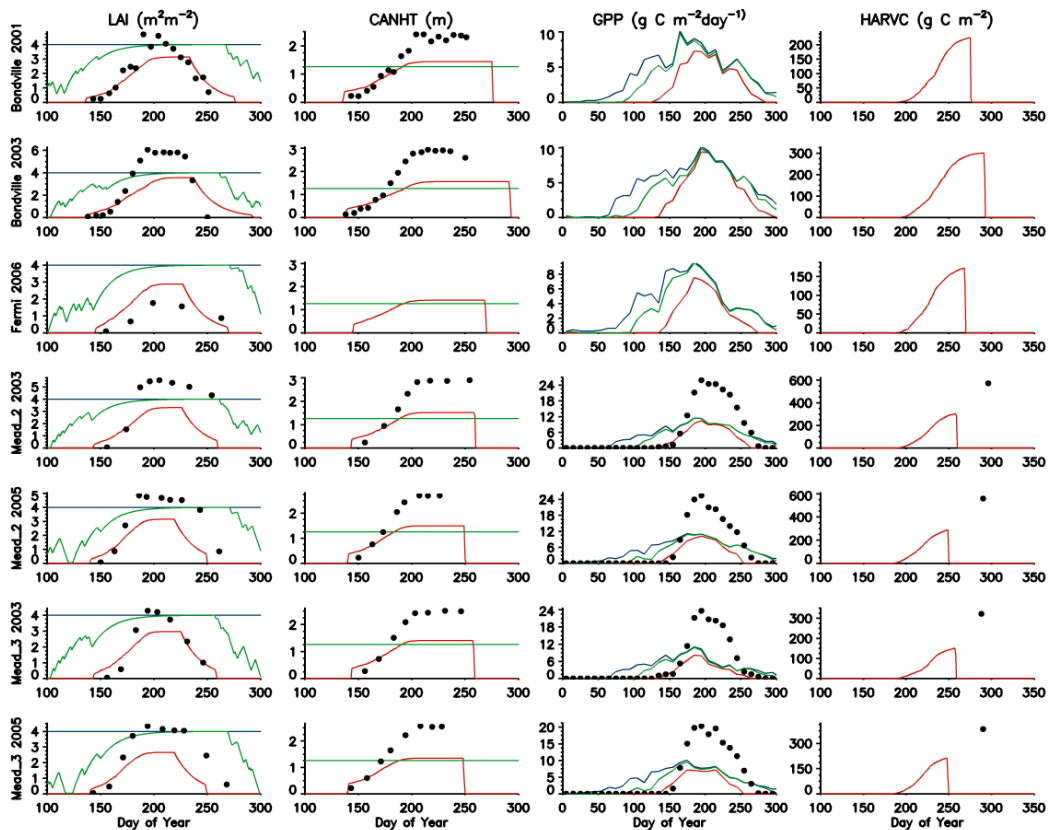
**Figure 9.** Simulated (solid lines) and observed (dots) ~~leaf-area-index~~ Leaf Area Index (LAI), ~~canopy height~~ Canopy Height (CANHT), ~~latent and sensible heat fluxes for Mead FLUXNET Site 2 in 2002~~ Gross Primary Production (~~left~~GPP) and ~~2004 Harvest Carbon~~ (rightHARVC) at a range of fluxnet sites and years. Simulations performed with JULES-crop crop type ~~soy-bean~~ Soybean (red), standard JULES ~~C3~~ C<sub>3</sub> grass plant functional type with phenology (green), and standard JULES ~~C3~~ C<sub>3</sub> grass plant functional type without phenology (blue).

## Soybean



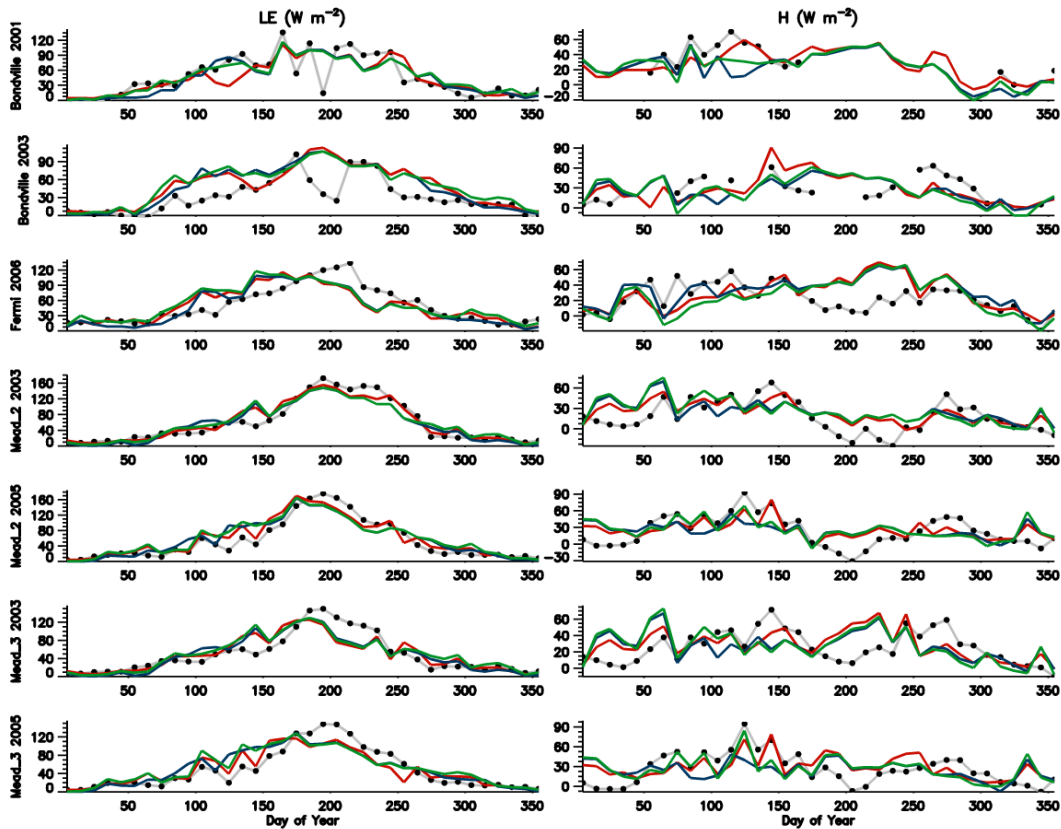
**Figure 10.** Simulated (solid lines) and observed (dots) ~~leaf area index, canopy height, latent~~ Latent (LE) and ~~sensible~~ Sensible (H) heat fluxes ~~for FLUXNET site Bondville in 2001 at a range of fluxnet sites and Fermi in 2006, years.~~ Simulations performed with JULES-crop crop type ~~maize~~ Soybean (red), standard JULES ~~C4~~ C<sub>3</sub> grass plant functional type with phenology (green), and standard JULES ~~C4~~ C<sub>3</sub> 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 C<sub>3</sub> grass plant functional type with phenology (green), and standard JULES C<sub>3</sub> 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  $C_3$  grass plant functional type with phenology (green), and standard JULES  $C_3$  grass plant functional type without phenology (blue).