Response to reviewers: gmd-2018-210

1 General notes to all reviewers

We thank all the reviewers for their thorough reading of the manuscript and insightful and helpful comments.

One common theme in all three responses is that we have not described the aim of the paper with sufficient clarity. We address this serious deficiency in the version of the manuscript submitted with this response, and thank the reviewers for drawing our attention to it.

Our overarching aim is to illustrate why it is useful to include FIFE in any collection of evaluation work on soil moisture stress in JULES. The FIFE dataset provides a clear example of where the current model parameterisation is unable to capture the diurnal cycle of GPP and transpiration during dry periods in this vegetation type, which is useful for testing model extensions. However, we did not mean to imply that any model improvements could be based on this dataset alone.

The availability of large, standardised data collections such as FLUXNET have revolutionised the evaluation of land-surface models against site data. Models and proposed extensions can be tested for a wide variety of climate regimes and vegetation types, and this is vital for making sure that they perform well on the global scale. The more sites that are considered in any particular study, the less detail can be covered on any one particular site in that study. Some single site experiments, such as FIFE, have an important contribution to make, although with the need for a proper understanding of the limitations of the dataset (for example, any conclusions drawn from this dataset should be robust to the large LAI uncertainty). Therefore, more detailed analyses of data from one site, such as ours, can help inform the more comprehensive multi-site analyses which are vital for model development, and GMD is the ideal place for both kinds of studies.

There are two studies underway so far which use the contents of this preprint, which provide good illustrations of how this paper can benefit future work. One of these studies is a comprehensive evaluation of JULES across many biomes involving 40+ authors. The other study evaluates an extension of JULES which incorporates optimisation arguments into the treatment of soil water stress in JULES, considering a wide variety of sites. In both cases, it was only practical to include FIFE because they could use the results from our study - given how many datasets they both include, they could not have devoted the time (or space in their manuscript) for going into this much detail on one site.

Suggested change to manuscript:

We have substantially redrafted the manuscript to make the aim of this study more clear, particularly the conclusions section. We have replaced the previous title ***Revisiting the First ISLSCP Field Experiment to evaluate water stress in JULESv5.0*** with

How can the First ISLSCP Field Experiment contribute to present-day efforts to evaluate water stress in JULESv5.0? , which makes the point that this paper is not aiming to be a comprehensive model evaluation on its own. We have also added a new section: ***Can the FIFE dataset make a useful contribution to current-day JULES evaluation and development work?*** , where we explicitly the describe the contribution the FIFE can make, while stressing that it should be used in conjunction with a large number of other datasets.

Summary of the new plots added, to address the reviewers' comments:

- Leaf water potential observations on four days, from Kim and Verma 1991.
- Calibrating the parameters in the ci calculation (f0, dqcrit) with a new observational dataset, from Lin et al 2015.
- Sensitivity of GPP to systematic variations in f0, dqcrit.
- Effect on GPP of imitating a 50% and 75% reduction in the g1 parameter in the Medlyn et al 2011 model (also shown is a plot showing how well the parameterisation used in JULES is able to fit the Medlyn parameterisation).
- How GPP, net canopy assimilation and latent heat flux change when replacing the Vcmax temperature distribution in the repro-cox-1998 configuration (we also show a plot of the Vcmax temperature distributions being tried out)
- Diurnal cycles of air temperature, leaf temperature and vapour pressure deficit
- Diurnal cycles of model transpiration and model evaporation (from canopy and surface/soil moisture stores).

2 Response to Reviewer 1

Williams et al. explored parameterising three different configurations of JULES to capture the diurnal cycle of GPP, net canopy assimilation, and latent heat flux during the dry spell at FIFE site 4439, Kansas, US, in 1987. They chose this site because it is of historical importance to the JULES community, having been used to develop the parameterisation of water stress in the model, but also because of the wealth of data collected there during 1987-1989. Out of the three configurations they tested, the authors found that the repro-cox-1998 was most successful at capturing the site fluxes, i.e. the closest approximation to the original Cox et al. 1998 model. Despite incorporating physical processes which are not supported by observations at the site (e.g. Vcmax declining at leaf temperatures above 32°C), this configuration is heavily tuned to the site data and mimics the model historically used to derive the JULES' parameterisation of water stress (i.e. Cox et al. 1998). The two less successful configurations both embed more sophisticated and mechanistic representations of the canopy, soil, and radiation modules; however, they are not run with the same PFT-specific parameters that were used in repro-cox-1998.

Overall, the authors' results seem to highlight the need for: (i) more coherent / less error-ridden site forcing data, (ii) more thorough evaluation at different stages of model development with regard to the assumptions in calibrating vegetation parameters. As presented, it is unclear what novel advances to the literature these broad conclusions brings. Nevertheless, there are interesting elements within the study, such as the author's effort to test three different configurations of a single model, representing different levels of complexity, with a variety of data for a specific PFT. For the value of those elements to clearly appear to the reader and for this manuscript to be ready for publication, I believe major revisions are necessary. It is especially important in revision that the authors reorganise their manuscript to more clearly demonstrate their findings. It is likely that separating the result and discussion sections will help the authors to more clearly present the paper's findings. In particular, thinking beyond the JULES community may help them articulate their findings - why would a developer of another LSM care about what is in this manuscript? Could more process-level interpretation arise from the simulations? But also, what are the advances for the JULES model community? If this is meant as a benchmarking type of effort, where is the performance evaluation? The latest more sophisticated configurations appear to perform "worse" than repro-cox-1998, so should JULES swap back to repro-cox-1998 for C4 grasses?

We thank the reviewer for this feedback, and have revised and reorganised the manuscript to address these points. In particular, we have redrafted the section in the introduction that outlines the aim for the study. We have also separated the results and discussions section into more sections, and rewritten the conclusions in order to answer these requests.

The reason we have presented three different configurations is not because we are looking at the effect of different levels of complexity or because we are looking at which is 'better' or 'worse'. Rather, we are using these configurations to explore whether this dataset would be a useful addition to the collection of datasets being used to evaluate the soil moisture stress representation within JULES and whether it needs improving. We realise that this was not made clear in the original version of the manuscript and we have rewritten the relevant sections (particularly the second half of the introduction and the conclusions).

It is unsurprising that the repro-cox-1998 configuration fits the net assimilation and evapotranspiration measurements at FIFE best, since it was tuned to these particular measurements. In contrast, the global-C4-grass configuration was designed (in Harper et al) to give good performance for C4 grass across the world. For this reason, it is generally inadvisable to adjust a PFT parameterisation that is believed to be broadly valid at the global scale, by instead one that is tightly tuned to a very specific location. We have described this point more explicitly in the new section ***Can the FIFE dataset make a useful contribution to current-day JULES evaluation and development work?*** , where we stress that model parameterisations need to work globally, which means that they need to be calibrated against a wide variety of datasets. We give an example of good practise (Lin et al 2015) to further emphasise this point.

The importance of the repro-cox-1998 configuration in this study is the fact that it appears to correctly simulate a temporary drop in productivity during the middle of the day in the dry spell. Showing that this is for the wrong reasons (an unrealistic temperature dependence in Vcmax) is an important step in showing that the current version of JULES cannot correctly capture the diurnal water stress processes at this site. We have redrafted this discussion, and made sure that the reason for reproducing the Cox et al 1998 configuration is stated clearly and unambiguously in both the introduction and the conclusion sections.

We think that JULES community can benefit from careful use of this dataset, with full knowledge of its strengths and weaknesses (i.e. a more pragmatic approach then seeking “more coherent / less error-ridden site forcing data"). Our opinion is that the FIFE dataset is a good example of where complementary measurements have been taken (e.g. LAI), which has enabled a more thorough investigation of the uncertainty in these measurements (e.g. Kim et al 1989) than is available for many other datasets. We have edited the manuscript so that we discuss this in the new ***Can the FIFE dataset make a useful contribution to current-day JULES evaluation and development work?*** section and the conclusions section, and we have also added a comment about this to the model setup section.

While the main focus of this paper is to determine how this particular dataset can contribute to evaluating and improving a specific process in JULES, we think that other land surface models might also consider using this dataset their own evaluation work. All the arguments in the first half of the new ***Can the FIFE dataset make a useful contribution to current-day JULES evaluation and development work?*** section apply to all land-surface models. However, the model suite we provide to users to pre-process and run with the FIFE dataset is specific to the JULES.

2.1 Response to main comments from Reviewer 1

> This paper focuses on how well a model can simulate a C4 tallgrass prairie’s response to water stress. So, generally, what are the valuable lessons? Why does the model fail to capture the dry-down response (what mechanism)? What have the authors tested to capture the missing mechanism? Even if simply empirically? Why not also run the global-C4-grass and the tune-leaf simulations with the JULES parameters used in repro-cox-1998 to highlight where the process based differences play a role? Unless I have missed this analysis in the paper, I think the respective parameterisations are different enough to hinder a mechanistic understanding of why differences occur.

This point is also mentioned by reviewer 2, and has led us to rethink the collection of runs that we have presented this analysis. This study involved hundreds of runs, with different parameter combinations to really probe the relative contribution of different mechanisms. We therefore had to think of how to pick a limited set for the manuscript to illustrate the main points. We picked three main configurations: (1) repro-cox-1998 to investigate the results published in Cox et al 1998, (2) global-c4-grass to show what the current ‘best’ parameterisation of this vegetation type in global JULES runs would capture, and (3) tune-leaf, to check that model deficiencies we are seeing in the global-c4-grass simulation can not be remedied by making the vegetation parameters more appropriate for the vegetation at this site using site measurements of leaf properties etc. We then adjusted the tune-leaf configuration to show (a) the effect of the choice of vegetation to tune to (by changing from parameters tuned to A.g. obs to parameters that lay between the A.g. and P.v. obs), (b) varying the soil moisture at which vegetation started to become stressed, governed by p_0 (which could also be seen as a proxy for uncertainty in one of the soil properties, θ_{crit}) and (c) the canopy clumping factor a (which could also be seen as a proxy for uncertainty in the LAI). We also showed a version of tune-leaf where the sensitivity of stomatal conductance to VPD had been over-exaggerated, well beyond realistic leaf-level values. This aimed to demonstrate that even in this extreme (and unrealistic) case, the VPD dependence of canopy GPP was not sufficient to model fluxes in the middle of the day during the dry season. This set of 9 runs was designed to cover the main points we wished to illustrate in the manuscript.

However, we also state in the manuscript that the reason that the repro-cox-1998 has a more realistic diurnal cycle during the dry spell than the other configurations is because of its unrealistic Vcmax temperature dependence. We did test this explicitly in runs with varying Vcmax temperature dependences, but did not include the plot in the previous version of the manuscript. We have now added these extra runs to the manuscript, which are based on repro-cox-1998 but show different vcmax temperature relations. We hope that showing this explicitly strengthens the paper, as the claim that the repro-cox-1998 configuration gets the dry spell diurnal cycle right for the the wrong reasons is an important step in verifying that the current representation of water stress in JULES cannot correctly simulate the dry spell diurnal cycle.

Suggested change to manuscript:

- We have redrafted the sections discussing the motivation for each of the parameter combinations we illustrate.
- We have added new plots showing runs which demonstrate the impact of three Vcmax(T) functions, while keeping the other parameters the same as repro-cox-1998. This is to provide evidence for our claim that the temporary drop in the fluxes in the middle of the day in the dry spell in the repro-cox-1998 goes away when Vcmax(T) is replaced with versions that are more high temperature tolerant.
- We have also added 5 new runs exploring more combinations of f0, and dqcrit, which are the parameters that go into the JULES ci/ca calculation.

> Where they simply assert: ‘inherent uncertainties in key observables, such as leaf area index, soil moisture and soil properties’, could the authors attempt to constrain one of these, e.g. LAI? Otherwise, I fail to see the point if we simply end up concluding these data are too uncertain to evaluate against.

We agree that the uncertainty in LAI has an important effect on the confidence we have in the model water and carbon fluxes. As described above, varying the canopy clumping parameter a is a proxy for the effect of varying LAI on model GPP, as it has a similar effect on the canopy radiation scheme. This is currently mentioned when the canopy clumping factor is first introduced and when the results from the runs varying the clumping factor are described. Similarly, varying the parameter p0 can be considered as a proxy for varying the critical soil moisture.

Suggested change to manuscript:

We have clarified the paragraph describing the runs which vary the clumping factor, including stating explicitly that these results mean that 'The error in LAI for this site therefore has a large impact on the modelled canopy carbon fluxes.'

Or, given one of the paper's aims to 'demonstrate how the wealth of data collected at FIFE and its subsequent in-depth analysis in the literature continues to be a valuable resource for the current generation of land-surface models', what are the immediate next steps the authors intend to make to exploit these data to improve the JULES model, without data related uncertainty hampering model development?

In this paper, we aimed to show that the model cannot currently capture processes governing the dry spell diurnal cycle in GPP and ET at this site, and that this conclusion is robust to the sources of uncertainty in both the data used to force the model (e.g. LAI) and the model parameters (e.g. Vcmax temperature dependence). The next step is to make this analysis easy to repeat , as we have done by providing the rose suite that accompanies this paper (rose is the scheduling software package typically used with JULES). As described above, this is currently being used in a comprehensive evaluation of soil moisture stress in JULES, which is based on a wider variety of site datasets. It is also being used (again in conjunction with lots of other site datasets) to evaluate a model extension, which includes a more sophisticated VPD dependence.

Suggested change to manuscript:

We have included a description how this work will be built on in practise to the new ***Can the FIFE dataset make a useful contribution to current-day JULES evaluation and development work?*** section:

> ...although the data is easily downloadable, well documented and in common file formats, is still needs to be manipulated into a format that can be used in JULES runs. We aim to address this issue by providing a suite that can be used to pre-process the FIFE data and run JULES with the configurations described in this manuscript (see the 'code and data availability' section). This aim is central to the provision of this manuscript. FIFE is the first 'JULES golden site', a concept was launched at the annual JULES meeting 2018. A JULES golden site is a site targeted by the JULES community because it can help address one of the key science questions facing JULES and has high-quality observational data that can be used to drive JULES and evaluate the output. It creates a network of researchers within the JULES community with experience of how this site can be exploited for JULES development, with input from site investigators. A key component is the provision of shared runs and evaluation datasets, which can be gradually expanded and improved.

Far more evidence is required to substantiate some of the points/arguments made to explain why the model is failing. As currently presented, they are purely speculative. For example, the authors speculate that an empirical link between leaf water potential and Vcmax/Jmax could improve models simulations. It would be an advance to the literature to actually show such a model (given they are relatively trivial to implement, e.g. Zhou et al. 2013, AFM; Kim and Verma 1991a, AFM), or at the very least, link more explicitly to literature that has done this (e.g. Tuzet et al. 2003, PCE; Zhou et al. 2013, AFM). Further, it would be useful to discuss the mechanism behind a direct limitation of leaf water potential on Vcmax and/or Jmax.

Suggested change to manuscript:

We have added a new section to address these points: ***What potential model developments could improve the diurnal cycle of JULES GPP at this site?*** . This goes through much more systematically the possible ways that JULES could be changed to capture the diurnal cycle of GPP during the dry spell than we had in the manuscript previously, and more clearly distinguishes between what we can conclude from this analysis, what is implied by this analysis and what is speculation.

It includes a discussion of how Zhou et al. 2013 and De Kauwe et al. (2015) allow the g1 parameter in the Medlyn et al 2011 stomatal conductance model to vary with soil moisture. We then present two new model runs, which show the approximate effect that multiplying the unstressed g1 by 0.5 and 0.25 would have on these JULES runs, if the Medlyn stomatal conductance model was used in JULES. This demonstrates that allowing c_i to depend on soil moisture would be one way to improve the diurnal cycle of JULES GPP at this site. We then go on to discuss other possibilities, including adding an explicit leaf water potential dependence (including Kim and Verma (1991a), Kim and Verma (1991b), Tuzet et al. (2003), Sperry et al. (2017); Eller et al. (2018), Tardieu and Davies (1992); Dewar (2002); Huntingford et al. (2015)) and leaf rolling. We also mention the technical issues around modelling leaf water potential explicitly in JULES.

We attempted to implement the Kim and Verma 1991b model for A. gerardii and P. virgatum by applying their factor to net leaf assimilation, in place of the JULES beta function, using leaf water potential observations from Kim and Verma 1991a. The result is shown in Figure R1 below. We are only able to do this for the four days with leaf water potential observations. We have not included this in the manuscript because we feel this does not add an extra information beyond what was presented in Kim and Verma 1991b, which we have already summarised in this section.

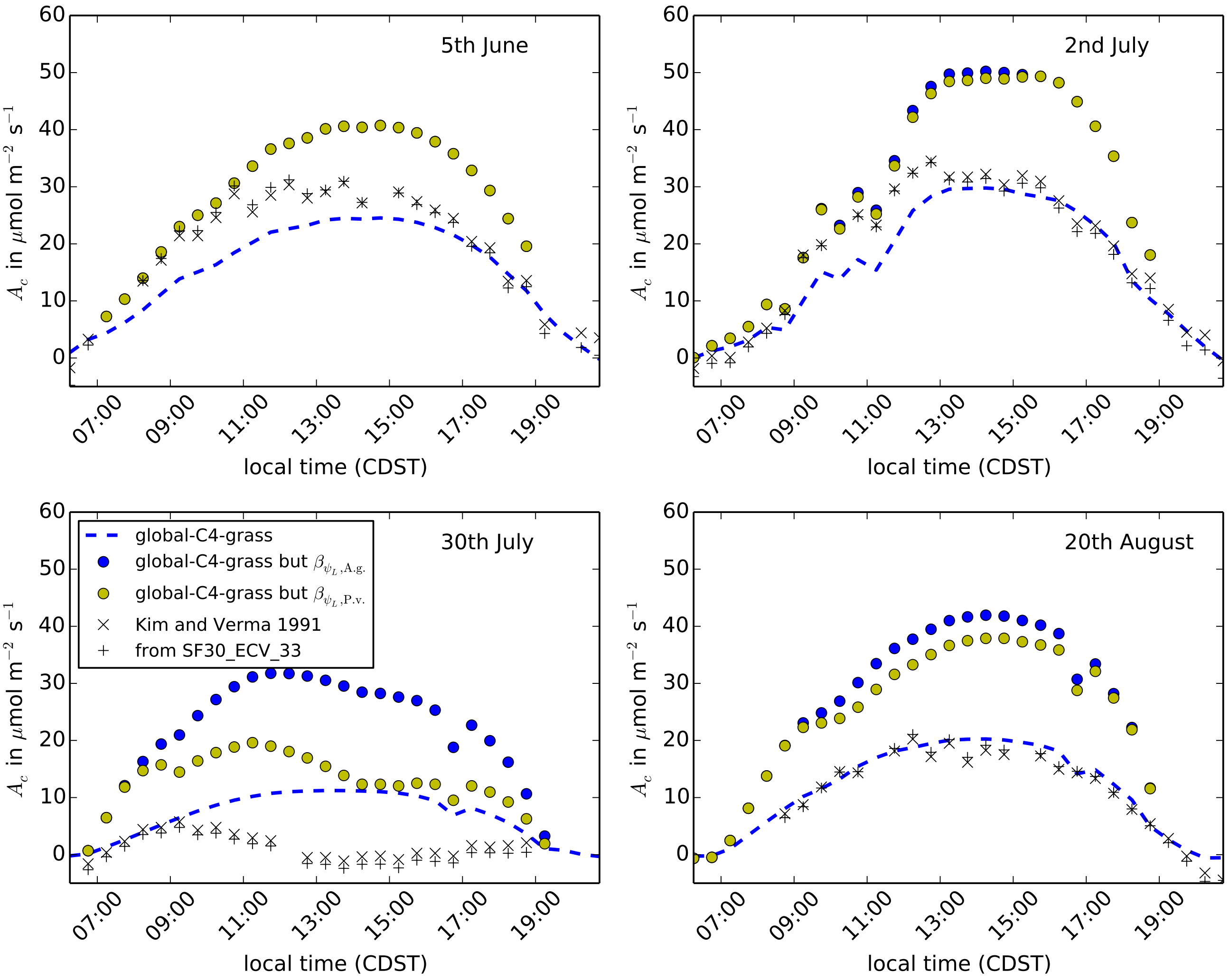

Figure R1. Net canopy assimilation for days where leaf water potential observations were given in Kim and Verma 1991a.

Suggested change to manuscript:

New section ***What potential model developments could improve the diurnal cycle of JULES GPP at this site?*** which contains some material from the previous version of the manuscript (but better explained) and also

- plots of diurnal cycle of air temperature, leaf temperature and specific humidity deficit, to refer to when arguing that the temperature response in the repro-cox-1998 runs is successful because it acts as a proxy for the specific humidity response.
- brief discussion of why including an interaction between soil moisture and specific humidity deficit could help the model reproduce the diurnal GPP cycle
- plots using 2 new model runs, which mimic the behaviour of decreasing g1 (g1 decreases in Zhou et al. 2013 when soil moisture is limiting)
- brief discussion of why leaf water potential is another way to combine the effects of soil moisture and specific humidity deficit
- brief mention of some models which include a leaf water potential dependence

It is unclear why the authors feel like the influence of VPD is negligible in the existing approach in JULES (lines 6-8, p.11), given that increasing VPD would drive a reduction in Ci? Indeed, in the last paragraph of Section 3.2, they show that for tune-leaf VPD influences GPP via this mechanism on both the 30th July and the 11th August. They also show that this mechanism alone doesn't have the flexibility to reproduce the observations. For all the days presented in Figure 13, it would be interesting to also plot Ac / E (the transpiration can simply be derived from the latent heat) relative to the declining soil moisture (or/and time), to see where the relative constraint is greater (on A more than E or vice-versa?) which might help further understand why the model is failing for the more extreme dqcrit

The dependence of GPP on ci in these runs is pretty low anyway, even after tuning to observations, as shown in Figure 5 (much lower than, for example, C3 grass from the global C3 grass configuration in Harper et al, due to the different implementation of C3 and C4 photosynthesis in JULES).

This extreme dqcrit shown in the previous version of the manuscript is not realistic, and is only shown in Figure 13 (old numbering) to demonstrate that even in this unrealistic regime of parameter space, there is almost no effect on GPP in three of the four days shown, and on the other day (30th July), there is a threshold behaviour, where GPP collapses to zero for a time, and is almost not affected apart from this. This can be understood from examining the ci equation in JULES (i.e. the suggested Ac/ E analysis is not the best way to illustrate this).

However, we appreciate that we have not done a good job of communicating the main result (i.e. that JULES can't capture the temporary drop in GPP in the middle of the day, regardless of what values of f0, dqcrit are used in the calculation of ci if they are also consistent with leaf-level observations in unstressed conditions).

Therefore, we have re-thought the way that we perform this part of the analysis. We (a) use another, better, dataset of measurements of unstressed C4 grass in the Konza prairie, from Lin et al 2015 which enables us to better constrain the parameters in the default tune-leaf configuration and (b) frame the analysis as a sensitivity test, where we look at the behaviour of GPP for three different combinations of f0 and dqcrit, which vary more systematically, rather than just showing what happens for an extreme dqcrit and (c) include two more combinations of f0, dqcrit, which mimic the behaviour of g1 decreasing under water stress (as described above).

Suggested change to manuscript:

- Used a new dataset to constrain the parameters that go into the JULES ci/ca calculation - figure 6 (new numbering)
- Systematically varied dqcrit, while staying consistent with this dataset, to show that a different f0, dqcrit combination would not improve the fit to the canopy fluxes - figure 14 (new numbering)
- Varied f0, dqcrit to mimic the behaviour in Zhou et al 2013, to show that if these parameters varied over the course of the run (because of, say, soil moisture) then this would provide a much better fit to the canopy fluxes - figure 15 (new numbering)

It is clear that FIFE site 4439 has historical value for the JULES community and that a lot of data is available. I am uncertain, though, as to how representative of the C4 grass PFT or the tallgrass prairie vegetation in general it is? Could the authors elaborate on this point, perhaps in the discussion?

This is a very good point. Part of this would be addressed by including this site as one of a large dataset, as that protects against overtuning to one particular site (as discussed above, we have stressed this point more strongly in the newer version of the manuscript). So it should only be used as one of many examples of a C4 grass PFT. FIFE site 4439 was representative of tallgrass prairie vegetation in terms of its species distribution and having been recently burned (see section 2.3) but not in terms of the fact that it was fenced off and hence ungrazed. Also, tallgrass prairie is has evolved in regions where it has had to cope with strong seasonal water limitation - this makes it a very interesting of example to study, particularly as we are interested in the interaction of soil moisture stress and atmospheric VPD controls.

Suggested change to manuscript:

We have added a discussion of why adding a tallgrass prairie site to multi-site evaluation dataset is useful:

> While, at one time, tallgrass prairie extended over 10% of the contiguous United States Fierer et al. (2013), it has declined 82-99% since the 1830s due to agricultural use (Sampson and Knopf, 1994; Blair et al., 2014a). However, grasslands in general (including other grass- and graminoid-dominated habitats, such as savanna, open and closed shrubland, tundra) cover

> more terrestrial area than any other single biome type (up to 40% of Earth's land surface (Blair et al., 2014a)). It is therefore important to include lots of examples of grasslands in any global analyses of vegetation responses to changing conditions. The Konza Prairie LTER site, where FIFE was based, has been used extensively to investigate the dynamics and trajectories of change in temperate grassland ecosystems, including drivers such as fire, grazing, climate, nutrient enrichment (see Blair et al. (2014b) for a review).

Why is this site a good proxy to calibrate the model for this PFT, in particular considering the variability of the site data?

In global JULES runs, vegetation at the FIFE site would be modelled as 'natural C4 grass'. We would not recommend that the JULES 'natural C4 grass' PFT parameters get calibrated to this site - they are chosen to get good performance globally for this PFT, particularly in terms of global distributions of this PFT when the dynamic vegetation model within JULES is switched on. Since we do not consider the dynamic vegetation model at all, a discussion of how to improve the parameters in the C4 grass PFT would be difficult to add to this manuscript without adding a lot of extra explanation which would not be relevant in the rest of the paper.

Suggested change to manuscript:

As described above, we have clarified the aims in the paper so that it is clearer that we are not proposing any changes to the global C4 grass parameters.

And is there any indication that it behaves like any other C4 grass site would during a dry spell? If this cannot be shown, I would encourage the authors to reword statements like '... FIFE observations were used to derive the original soil moisture stress parameterisation that was incorporated into JULES. This therefore makes FIFE an ideal test case for evaluating and improving this process.'.

Suggested change to manuscript:

We address the question of why FIFE is an ideal test case for evaluating improving water stress in JULES in the new section ***Can the FIFE dataset make a useful contribution to current-day JULES evaluation and development work?*** but we stress that this is only alongside a comprehensive range of other datasets. For example,

> A global land-surface model such as JULES needs to perform well for a wide range of climate regimes, time scales, spatial scales and vegetation types. Model evaluation or development work needs to represent this variety. The availability of comprehensive databases, such as FLUXNET (Baldocchi et al., 2001) and the TRYKattge et al. (2011), have revolutionised land-surface science by giving easy access to observations from a wide variety of sources, in a common format. ... When adding a new process to a global land-surface model, it is important to tune new parameters to a comprehensive range of datasets. For

> example, as mentioned in Section 3.3, Lin et al. (2015) use data for 314 species from 56 sites across the world to tune the new g1 parameter introduced in the Medlyn model of stomatal conductance for key plant functional types. This breadth of sites and vegetation types is essential.

and in the new version of the conclusion,

> FIFE can play a role in JULES evaluation and development only as one small component of a comprehensive range of datasets, covering different climate regimes, time scales, spatial scales and vegetation types... Confidence that the model is capturing key processes is necessary if the model is being run into new regimes, such as when forced with climate projections. This ability to disentangle and evaluate individual processes emphasises the value that intensive experiments such as FIFE have towards the larger modelling community evaluation efforts.

The authors could also more clearly demonstrate the impact of key assumptions. The following is an important point concerning the physical representation of the response of Vcmax to leaf temperatures above 32°C in Cox et al. (1998): 'However, as discussed in Section 2, this temperature response is not supported by observations in Knapp (1985) or Polley et al. (1992). Therefore, it appears that, while the model is successfully capturing the shape of the diurnal cycle during the dry period, it is not achieving this with the correct physical process.' It would be easy for the authors to test this, simply by swapping the temperature response function and determining if this statement is true or false.

Suggested change to manuscript:

As described above, we have added plots showing 3 runs that swap the Vcmax temperature response curve in the repro-cox-1998 configuration with other temperature distributions (these runs had formed part of the original work, which is why we were able to state that the repro-cox-1998 relied on its temperature dependence to reproduce the temporary drop in canopy assimilation during the day in the dry period, but we had not backed up this claim by showing the plots in the previous version of the manuscript).

Finally, I would like to thank the authors for making all of the code and data available. Interactive Their careful description of the steps taken to set up the simulations is also appreciated.

Thanks, we very much appreciate that feedback, and we hope that the code and data will continue to be reused in other studies.

2.2 Response to minor comments from Reviewer 1

Lines 28-30, p.2: the precision that ‘changing p0 can be considered a proxy for chang- ing the critical soil moisture’ which appears lines 8-9, p.16, could probably appear here, or at least in Figure 1’s caption

Varying this parameter does act as a useful proxy for varying the critical soil moisture theta_crit in our runs. However, it is not designed to do this (it is actually meant to represent differences between different vegetation types when grown on the same soil), so adding this in to this theoretical description of the JULES soil moisture parameterisation at this stage would not assist clarity. theta_crit is a hydraulic parameter of the soil (defined through soil potential). As we discuss, varying p0 is interesting in its own right, as a way to parameterise the response of the FIFE vegetation to soil moisture. We discuss the additional use of varying this parameter as a way of getting a handle on the effect of uncertainty in theta_crit in section 2, when we are discussing the uncertainty in the soil parameters and in section 3 when we discuss what we can conclude from varying p0. This works because we are just running the model at this one location, and have one vegetation type - the interpretation of anything else would start to get convoluted.

Varying the canopy clumping parameter a is a similar case: this parameter has a physical interpretation, and could not be well constrained by the available observations. Therefore it is useful to look at the effect of the uncertainty in its own right. In addition, it can also give us insight into how GPP would differ if a different LAI was used, since more canopy clumping has a similar effect in the radiation scheme to less LAI (although the effect on leaf respiration differs).

Lines 1-2, p.5: even though the differences in evaporative schemes aren’t the focus here, can the authors estimate how those might influence their conclusions?

We have added plots which split the model evapotranspiration into the transpiration and evaporation components. While this does not influence our conclusions, evaporation would be interesting to investigate at FIFE in a future study. In this case, we would use all time steps, rather than those selected in this analysis.

Suggested change to manuscript:

New plots added with model transpiration and evaporation.

Section 2.3: how is the tune-leaf configuration calibrated exactly? What is matched for in the calibration process? What does ‘approximately representative of the dominant species’ mean? How so?

The calibration of the tune-leaf configuration against site observations involves tuning the JULES parameters given in table A2. We outline how each of these parameters is calibrated in section 2.3. As described, some parameters can be calibrated directly to parameters given in literature, e.g. specific leaf area and the ratio of leaf nitrogen to leaf dry mass. However, many need to be calibrated in combination with eachother: plots 3,4,5, where we are calibrating to the equivalent quantity in JULES.

Suggested change to manuscript:

We have improved the calibration of the ci parameters f0 and dqcrit by using a better observational dataset. This has allowed us to greatly simplify the description in the manuscript, which we hope has assisted in the overall clarity. We have also clarified the description of figure 5 in the text and caption.

Lines 9-10, p.7: it is unclear to me why the burned plot was not water-limited. Could the authors please elaborate?

‘not limiting’ is a quote from their paper, from their experiment description (note that this just applies to data they took in the period May-June). We looked at whether this statement is consistent with their leaf potential observations in section 2.3.2.

Suggested change to manuscript:

We have edited the text to make it clear that ‘not limiting’ is a quote from Knapp et al:

> Therefore, we use the observations from the burned plot in Knapp et al (1985) during May-June 1983, when they describe water availability as ‘not limiting’ (we will investigate this claim in more detail in Section 2.3.2)

Lines 31, p.7: why do the authors assume that the best parameter set is a composite of GMDD two species’ parameter sets, given the non-linear response of photosynthesis to plant traits?

Our default tune-leaf configuration is based on A.g., so does not suffer from this issue. However, we do use a composite A.g./P.v. configuration to investigate the effect that considering other species might have on our conclusions. We absolutely agree that the interpretation of this composite configuration is clouded by the non-linearity of the response of photosynthesis to plant traits. However, we feel it is sufficient for our purposes, just to give an idea of the sensitivity.

Also, note that, as described above, we do not consider either of these two configurations to be the ‘best’. Global-C4-grass continues to be the appropriate configuration to use for this site in global studies.

Line 10, p.8: I don’t understand which mean the Al-Ci curves were normalised against Lines 11-13, p.8: can the authors demonstrate this claim or refer to studies that do?

The normalisation for the observations is the mean A_l at high ci (i.e. $>$150) for each individual curve. We have clarified the identification and normalisation of these curves, both in the text and in the caption to figure 5.

The water stress factor β cancels in the model Al when normalised in this way, because Al in the model is linearly dependent on β (assuming that water stress is constant over the short period the curve was taken at - a very good approximation). Leaf nitrogen approximately cancels in the model Al when normalised in this way because the model Rubisco-limited and the model PEPCarboxylase limitation rate are both proportional to leaf nitrogen content. The light limited rate is not, which only pick points above a light threshold for this part of the analysis, so that the importance of the light-limiting rate is minimised (although not zero) in these model points. Each curve corresponds to measurements taken on the same leaf, so the leaf nitrogen content is constant for that curve. The strength of this approach can be seen in the low spread of the model points, which makes it easier to calibrate to the observations. (most of the remaining spread is due to the change in leaf temperature while the measurements for the curve are being taken)

Suggested change to manuscript:

The text description and caption now read

> ... if we are to use these observations to calibrate the unstressed model parameters, we have to process them in such as way as to minimise the influence of the parameterisation of water stress in the model.
>
> To achieve this, we identified individual net leaf assimilation (A_l) versus leaf internal CO_2 concentration (c_i) curves from the FIFE_PHO_LEAF_46 dataset for *A. gerardii* and *P. virgatum* (using the observation time and leaf area). We normalised each A_l-c_i curve using the mean A_l for $c_i > 150\mu$ mol CO_2 (mol air)$^{-1}$ for that curve. We then selected A_l-c_i curves with mean incident radiation greater than 1200 μmol PAR m^{-2} s^{-1}. This procedure minimises the dependence on water stress or individual leaf nitrogen levels, since these factors approximately cancel out in the relations used internally in JULES when they are manipulated in this way. We can then use these normalised curves to calibrate the model A_l-c_i response at low c_i. For *A. gerardii* and, to a lesser extent, *P. virgatum*, this leads to a decrease in the initial slope of the A_l-c_i curve (Figure 5).

and

> Black crosses: A_l-c_i curves for *Andropogon gerardii* (left) and *Panicum virgatum* (right) from FIFE_PHO_LEAF_46 (Polley et al 1992), normalised by the mean A_l of the data points with $c_i > 150\mu$ mol CO_2 (mol air)$^{-1}$ in that curve. Only curves with mean incident PAR greater than 1200 μmol PAR m^{-2} s^{-1} have been used. Coloured points: normalised A_l calculated from observed c_i and incident PAR for each data point in the curve and the mean T_{leaf} observation for each curve, using the JULES relations. The JULES parameters are taken from the `repro-cox-1998` configuration (red triangles), the `global-C4-grass` configuration (blue circles) and fits to A. g. data (`tune-leaf` default configuration, cyan diamonds) and P. v. data (yellow diamonds). Model points have been calculated using the Leaf Simulator package.

Lines 30-34, p.8: does this mean the dark respiration at Tleaf different to 30°C is then still scaled according to the temperature dependency in JULES (if so, can the authors justify this approach)? Or does the scaling follow Polley et al. (1992)?

In JULES, dark leaf respiration is proportional to V_{cmax}. We calibrated the temperature dependence of model V_{cmax} to the Knapp net assimilation observations, taken at different temperatures. Therefore, the temperature dependence of dark leaf respiration in JULES is different to the temperature dependence in Polley 1992 (a rectangular hyperbola). This is illustrated in Figure 7 (old numbering) (note also that JULES has light-inhibited respiration - see section A6 for a more detailed description). This difference between the JULES leaf respiration at higher temperatures and the available observations does introduce an uncertainty, and is one of the reasons that we consider both GPP and net canopy assimilation in the results section. However, this uncertainty is relatively minor (also note that (a) leaf temperatures in these runs only reach a maximum 42°C and (b) the Polley analysis has just 2 data points which are above 39°C). This uncertainty does not affect our conclusions.

Lines 4-14, p.9: that whole paragraph could be moved to the beginning of section 2.3.1, thus the text that follows might be less confusing for the reader

We were able to move the second part of the paragraph to earlier in the section, but we couldn't get the rest of the text to fit in earlier, since it deals with the effect of not including S. nutans in the calibration lots of different parameters, according to the Polley 1992 study, all of which get discussed at different places in this section. Therefore moving this section would require lots of repetition which would reduce clarity.

Suggested change to manuscript:

We have moved the text

> Polley et al. (1992) also found that there was 'no apparent relationship' between leaf temperature and net leaf carbon assimilation in their measurements of A. gerardii, S. nutans and P. virgatum, taken at ambient temperatures between 24.1°C and 47.8°C . They speculate that the difference between their results and the temperature relations found by Knapp (1985) is due to seasonal acclimatisation. On the one hand, this supports the change from using the rapidly varying Vcmax with temperature in this regime in both the repro-cox-1998 and global-C4-grass simulations to using the relatively more stable tune-leaf parameterisation. On the other hand, it implies that an even more stable parameterisation would be desirable. We will revisit this issue in Section 3.

to earlier in the section (and also redrafted it to get it to fit in).

Line 22, p.9: missing the work 'water' after 'vegetation. Leaf'

Thanks for pointing out this mistake. We have corrected it.

Suggested change to manuscript:

Changed 'leaf potential' to 'leaf water potential'

Lines 22-23, p.9: maybe specify what other factors can affect leaf water potential

In the new section ***What potential model developments could improve the diurnal cycle of JULES GPP at this site?*** we have added a more detailed description of leaf water potential, what affects it and how it can be modelled.

Suggested change to manuscript:

Added

> leaf water potential is affected by both soil moisture (water supply) and VPD (atmospheric water demand)... Leaf water potential is not currently modelled explicitly within JULES. Typically, in plant hydraulic models, leaf water potential is calculated assuming a steady-state water balance, using the soil water potential, transpiration, and leaf-to-root and root-to-soil resistance terms (as in, e.g. Newman et al 1969). Adding this to the JULES code is technically non-trivial as water stress is currently applied to leaf-level processes before transpiration is calculated. Also, modelling the plant resistances would require additional input parameters, which would need to be constrained from observations.

Lines 1-2, p.15: is this observed during the dry period as well? Does this mean that it is constantly proportional through time?

Yes, approximately, according to the results from these two studies. The dataset we consider in this version of the manuscript also shows this approximate relationship (since the VPD dependence is small compared to the spread in ci)

Suggested change to manuscript:

Clarify this in the manuscript by comparing this result to the Lin et al dataset:

> Both Knapp et al 1985 and Polley et al 1992 found that leaf stomatal conductance g_s is proportional to the net leaf assimilation at this site. Their results are approximately consistent with the Lin et al 2015 observations, given the difference in ambient CO_2 levels and the weak dependence on VPD.

Lines 6-8, p.16: please add the missing words in the sentence

Thanks for noticing this.

Suggested change to manuscript:

We have changed the sentence

> It demonstrates the importance of ensuring that the threshold for water stress is consistent with the ‘unstressed’ leaf observations we tuned against, since using p0 =0 with these new parameters would have resulted GPP that is much too low the early growth period that we were using for tuning.

to

> It demonstrates the importance of ensuring that the threshold for water stress is consistent with the ‘unstressed’ leaf observations we calibrated against. Continuing to use p_0=0 with the newly-tuned unstressed parameters would have resulted in much too low GPP during the early growth period.

Line 3, p.17: missing ‘of’ before ‘the humidity response‘

Thanks for pointing this out. This is one of the sections of the manuscript which has been rewritten, so this sentence no longer exists in that form.

Lines 4-6, p.18: leaf rolling/folding implementation feasibility in a global model should at least be discussed in view of the existing literature and considering the author’s previous statement that ‘this behaviour cannot be modelled in the current version of JULES’ (line 28, p.11); the same goes for including leaf nitrogen

We do not know of any land-surface schemes which currently implement this process - since they couple to global climate and Earth System Models, they need to strike a balance between representing key processes, while avoiding the introduction of parameters that would be difficult to define across the globe. As a result, global land-surface schemes often simplify or neglect local processes in order to be more generally applicable in less well-measured locations. We believe leaf folding is in the group of processes that are currently neglected.

To our knowledge, no publications of JULES have attempted to change the PFT parameters governing the leaf nitrogen concentration over the course of the season, although one (Williams et al 2017) noted that this was a source of uncertainty when modelling maize, particularly during the senescence period.

(n.b. JULES does include a nitrogen cycle, which we do not switch on in this study. This uses nitrogen availability in the soil to limit carbon uptake.)

Suggested change to manuscript:

We have changed the statement ‘this behaviour cannot be modelled in the current version of JULES’ to be more explicit: ‘this behaviour is not implemented in the current version of JULES’.

and added this paragraphs to the ***What potential model developments could improve the diurnal cycle of JULES GPP at this site?*** section:

> Finally, another way to improve the diurnal cycle of GPP in the dry period would be to incorporate a parameterisation of leaf rolling. For example, effective leaf area available to the radiation scheme could be decreased during hot, dry weather. Kim and Verma 1991 attribute the residual overestimation of net canopy carbon assimilation on days during the dry period of their leaf water potential-based model to this effect. It would therefore be interesting to investigate the contribution that leaf rolling makes to the overall plant water use strategy. However, while the occurrence of leaf rolling/folding at the FIFE site has been recorded, the effect has not been quantified. This would be a necessary first step for modelling this process at this site.

Line 9, p.25: the authors should specify “for C4 grasses" or something equivalent

As part of the changes described above, the conclusions section has been rewritten, and this sentence no longer exists. However, we have added in comments elsewhere to stress that FIFE is a useful for looking at water stress in JULES only as one of a very large number of other sites covering lots of vegetation types e.g.

> FIFE can play a role in JULES evaluation and development only as one small component of a comprehensive range of datasets, covering different climate regimes, time scales, spatial scales and vegetation types.

Line 14, p.26: I believe this is the first time senescence is mentioned. Do the authors propose to do this via the leaf water potential parameterisation? Or do they envision it might somehow relate to a LAI phenology?

As described above, we have rewritten the conclusions section. The new version no longer contains a mention of senescence. It would be interesting in a future study to improve the way that the JULES phenology scheme models LAI at this site (at the moment, it gives a poor annual cycle, which we avoid in this study by forcing with LAI observations), and this could include drought-induced senescence.

Line 20, p.32: the approximation that soil evaporation can be neglected for days without rainfall seems rather big to me; have the authors considered including soil evaporation (though it isn't the focus of the study) to reduce the uncertainty?

All our model runs include evaporation from the soil moisture store, surface store and canopy. The latent heat observations also include both evaporation and transpiration. However, we wanted to minimise the influence of evaporation on our results and focus the discussion on transpiration, which is why we used the same procedure as Cox et al 1998 to pick timesteps.

Suggested change to manuscript:

Have added plots dividing the model evapotranspiration diagnostic into the transpiration and evaporation (from the soil moisture store, surface store and canopy) components.

Figure A4: the depth unit should appear somewhere in the plot

Suggested change to manuscript:

We have added the depth unit to this plot.

3 Response to Reviewer 2

This manuscript describes an evaluation of the JULES land model using field data from the FIFE dataset. Three simulations are presented: a replication of a simulation from an earlier model version, a standard simulation using the current version, and a tuned simulation using site specific parameters rather than global parameters. Numerous model intercomparison projects (MIPs) have been published in recent years, and one of the criticisms of these studies is the lack of adequate control in the experimental design. For example, models participating in a study may differ in forcing data, structure, and parameters, which makes attribution of differences in the results to these model characteristics difficult if not impossible. This study can be thought of as a three model MIP, and it features the same difficulty. Although the three models are all versions of JULES, they differ in multiple ways, making the interpretation of the results unclear. For example, simulations 2 and 3 differ due to the tuning of simulation 3 of multiple parameters for stomatal conductance and C4 photosynthesis, such as: SLA, leaf nitrogen, light response parameters, Vcmax temperature dependence, A-ci response at low ci, ci-ca relationship, dark leaf respiration - Vcmax ratio, p0 (water stress onset parameter), and canopy structure (uniformity). Figures 8-10 show that the site specific tuning exercise leads to large differences between simulations 2 and 3; in fact, these differences are larger under *unstressed* conditions than under stressed conditions. Moreover, while the tuned parameters should by design lead to better agreement with the observations against which they were calibrated (figures 3-7), they do not in general improve the simulation of GPP or An under unstressed conditions. I recommend to the authors to give the reader a better understanding of the individual impacts of this tuning exercise in the context of their effect on GPP and An. Which parameter changes improved the comparison, and which degraded the comparison? This is important to understand, more so because the agreement differs for the different days presented in the analysis.

As discussed in the response to reviewer 1 above, the work for this study involved hundreds of runs, to get a deep understanding of the model behaviour. One of the most difficult challenges we faced when writing this manuscript was how to present our key findings from this large number of runs in a coherent way. Therefore, we had to pick a subset of runs, choosing each carefully to illustrate a particular point.

These were based on three main configurations. The first, repro-cox-1998, was used to demonstrate that a previous study was able to fit this data very well (when tuned to it), but that part of this success relied on a process (temperature response of Vcmax) which is tuned in a way that makes it a poor fit to the physical process it is designed to represent. The second configuration represents a ‘standard’ configuration that would be used to represent this PFT in a global run. We show that this shows an unreasonable degree of water stress during a period where the vegetation should not be experiencing severe stress and that the shape of the diurnal cycle during the dry season is not well-captured. This could be because the generic C4 grass tuning parameter values are not suitable for the vegetation at the FIFE site or because the underlying parameterisations within the model are not adequate. In order to investigate this, we compare individual processes against FIFE observations and use the resulting tuned parameters in the tune-leaf configuration.

We then vary the tune-leaf configuration to see the impact of different plant species, varying canopy structure (or LAI uncertainty), soil moisture for onset of stress (which can be considered a combination of vegetation response p0 and soil properties theta_crit), to show that our conclusions are robust to what we have identified to be the key observational and parameter uncertainties. We were therefore able to show that the conclusion that the current version of JULES cannot capture the diurnal GPP cycle during the dry spell is robust to these uncertainties.

In the previous version of the manuscript, we then underlined that the model has an inadequate VPD response by inflating the VPD sensitivity to unrealistic proportions and demonstrating that even with these extreme parameters, the temporary drop in the dry season GPP diurnal cycle can not be modelled. We have replaced this section with a sensitivity test to systematically varying the VPD response, while maintaining consistency with unstressed observations (using a new observational dataset). We think that this is a clearer way to demonstrate the same point.

As a result of reading the reviewers' comments we have realised that the manuscript lacks an explicit illustration of the finding that the repro-cox-1998 gets the shape of the dry-season diurnal season correct due to its inaccurate Vcmax temperature dependence - we assert this in the manuscript, but did not include our evidence. We have therefore added extra plots, based on the repro-cox-1998 configuration, showing the effect of varying the Vcmax temperature dependence.

Suggested change to manuscript:

- Extensively edited the manuscript to make the motivation for each parameter combination clearer
- New sensitivity tests to the parameters involved in calculating the internal CO2 concentration - figure 14 (new numbering).
- added plots showing 3 runs that vary the Vcmax temperature dependence and keep other parameters the same as the repro-cox-1998 configuration
- Also added a plot showing how the effect of allowing the parameters involved in calculating the internal CO2 concentration to vary with soil moisture (this functionality is not included in the current version of JULES) - figure 15 (new numbering).

While it is subjective, I did not agree with the authors' statement that the model was "...able to successfully reproduce the net canopy assimilation and latent heat energy flux reasonably well through the season". Given this perhaps unsatisfactory starting point for unstressed conditions, I recommend to the authors to focus first on obtaining more credible results under unstressed conditions before addressing the model's response to drought.

We agree that representing the early season correctly is important and have tried to take full advantage of the relevant observations available at FIFE to investigate the model performance in this season. This focus here is whether both the repro-cox-1998 and global-c4-grass configurations are over-representing stress during this period, and after a careful consideration of performance of individual processes against observations and untangling compensations within the model, we are able to conclude that the default value of p0=0 does result in the model simulating a much too high degree of soil moisture stress during this period.

Suggested change to manuscript:

We have clarified the motivation for the tune-leaf configuration in the text.

The title indicates that the goal of the manuscript is the evaluation of water stress in the current version of JULES, thus my expectation was that the experimental design would isolate the behaviour of this parameterisation; however, this is not really the case.

We have changed the title to emphasize that this site can be used as part of a full evaluation of water stress in JULES in the future, and to make sure that the title does not give the impression this paper itself contains a full (multi-site) evaluation of this process in the model.

Suggested change to manuscript:

Have changed the title from ***Revisiting the First ISLSCP Field Experiment to evaluate water stress in JULESv5.0*** to ***How can the First ISLSCP Field Experiment contribute to present-day efforts to evaluate water stress in JULESv5.0?*** .

Only figures 11-13 show single factor analyses, and of those, only figure 11 directly examines the water stress parameterisation used in the model.

It is not possible to isolate the behaviour of soil moisture stress in *in-situ* observations for a clean comparison with the model without investigating factors such as the A-ci curve, Vcmax temperature dependence, LAI, canopy structure, soil properties, response to air VPD etc. Therefore we have to consider all these factors, and not just the shape of the soil moisture stress function.

Suggested change to manuscript:

We have clarified the motivation for each of parameter combination and explicitly showed how each one feeds in to our conclusions.

Figure 11 shows the results of varying the p0 parameter that determines the initial soil moisture value at which vegetation experiences stress. I recommend that the authors show a few actual lines rather than the spread of p0 = [0,0.4] to enable the reader to easily see whether increasing p0 increases or decreases GPP.

The p0 band is designed to demonstrate the uncertainty in GPP arising from the uncertainty in p0. The upper edge corresponds to the maximum value of p0 and the lower edge to the minimum. This is because increasing p0 increases the stress factor beta (fig 1), and therefore increases GPP (since GPP is proportional to beta). We use a band rather than a set of lines to show that this part of the analysis is looking at a key uncertainty, and keep it distinct from the sensitivity tests in figure 14 and 15 (new numbering), which plotted with lines.

Suggested change to manuscript:

We have added the information ‘lower limit corresponds to p0=0, upper limit to p0=0.4’ to the figure caption.

One might expect that water stress based on soil moisture would not exhibit large diurnal variation, and this is confirmed by these plots. Figures 8-10 show that the diurnal variation in GPP and An can be simulated (in this case by simulation 1) if a predictor having stronger diurnal variation (such as temperature) is used. However, the authors note that this type of parameterisation is not well supported ("The repro-cox-1998 simulation is more successful, but this response is mediated by a temperature dependence in leaf carbon assimilation which is not supported by observations") as shown by figure 4. At this point the analysis is basically complete, with no improvement in the diurnal cycle of carbon flux. This seems not to support the authors’ conclusions regarding outcome of the study (e.g. "FIFE provides an ideal case study for improving the model representation of water stress on carbon and water fluxes on a tallgrass prairie site") as no significant improvement was made aside from tuning the p0 parameter based on unstressed soil moisture conditions.

We intend the manuscript to show that FIFE would be an ideal test site (along with a wide range of other sites) for future work on new parameterisations that could be added to the model. We did not intend to claim that we have added a new way of calculating soil moisture stress to JULES ourselves. We have realised that we failed to make this clear in the previous version of the manuscript and have made major changes to address this.

Suggested change to manuscript:

As described above, we have edited the manuscript to make this more explicit, including changing the title, major editing to the second half of introduction, rewriting the conclusions and adding a new section ***Can the FIFE dataset make a useful contribution to current-day JULES evaluation and development work?*** .

The authors note that leaf water potential was used by authors of previous studies to simulate the diurnal cycle of GPP under dry conditions, leading them to conclude "JULES is not currently able to capture the diurnal cycle of net canopy photosynthesis at this C4 grass site, due to the lack of a strong dependence on the canopy vapour pressure deficit (indirectly or directly)", but this is largely conjecture and not actually tested by the authors of this paper.

We have written the new section ***What potential model developments could improve the diurnal cycle of JULES GPP at this site?*** to discuss methods that could be investigated for improving the diurnal cycle of GPP at this site during dry spells (requested by reviewer 1). As part of this, we now demonstrate explicitly that changing the parameters in governing the relationship between internal CO2 and VPD away from the unstressed values does help capture the dry spell diurnal GPP cycle.

Suggested change to manuscript:

Explicitly discussed which changes might help JULES capture the diurnal cycle of GPP during the dry season at this site and why.

Added runs which mimic a reduction in g1 during the dry season, to show that this could improve the fit to the observations.

Written more explicitly that we can not recommend changes to JULES based on one site alone, we can only discuss how these changes might impact this particular site e.g.

> A global land-surface model such as JULES needs to perform well for a wide range of climate regimes, time scales, spatial scales and vegetation types. Model evaluation or development work needs to represent this variety... When adding a new process to a global land-surface model, it is important to tune new parameters to a comprehensive range of datasets. For example, as mentioned in Section 3.3, Lin et al. (2015) use data for 314 species from 56 sites across the world to tune the new g1 parameter introduced in the Medlyn model of stomatal conductance for key plant functional types. This breadth of sites and vegetation types is essential

In summary, this manuscripts describes many of the issues that one encounters when attempting to constrain a model to field observations, such as uncertainty in measure- ments and spatial heterogenaeity. It highlights the fact that greater model complexity does not guarantee greater model fidelity. It also shows that site-specific model parameters may give significantly different results relative to global parameters. This is valuable information and worth presenting. However, that is not the stated focus of the manuscript, which is water stress and its improvement in JULES. To that end, I recommend to the authors to revise their title and to shift the focus of their discussion towards the actual content of the paper.

Suggested change to manuscript:

As discussed, we have changed the title, redrafted the parts of the text dealing with the motivation and conclusions of this study and added a new section to explicitly discuss the value of including this site in large multi-site comparisons, to address these concerns.

4 Response to Reviewer 3

The authors present three simulations of FIFE Site 4439 (Konza Praire, Kansas) utilizing three configurations of JULES, from Cox et al. 1998, Harper et al. 2016, and a third developed for this manuscript. The parameterizations are compared for sensitivity to changes in root-zone soil water, light availability, leaf temperature as well as for the relationship between intercellular CO2 and net assimilation. The results show that the two literature-based configurations may not capture observed relationships in site-level data (e.g. Polley et al. 1992, Knapp 1985). The simulations are next confronted with observation-based data of GPP, net assimilation, and latent heat flux from 8 days during 1987. Generally speaking, the Cox et al. simulation output tends to provide the best fit to these data. Lastly the authors present parameter sensitivity results (of GPP) for four "tune-leaf" parameters.

Strengths: (1) The authors very clearly explain the process by which they developed the tune-leaf parameterization and its differences with the Harper and Cox parameterizations. This includes Figures 3-5,7, which effectively demonstrate the fit provided to leaf-level data by the three parameterizations. (2) The authors show, across a small subset of observational data, that utilizing field-derived paramater values tend to degrade model performance (Figs8-10). This is an important (and not unexpected) finding that will merit further study.

We thank the reviewer for these comments, and agree that incorporating improved parameter values from field observations can often have surprising effects due to compensating errors (e.g. in Huntingford et al 2017, when they trialled a more comprehensive better leaf respiration dataset in JULES). This is a very interesting area of study, which is very important for trusting the underlying processes when we run the model in new regimes e.g. climate change studies.

Weaknesses: (1) Conclusions are not strongly based in the specific work conducted within this study. See comments.

As discussed at the beginning of this document, we realise that we have failed to clearly describe the motivation and conclusions of this study in the previous version of the manuscript.

Suggested change to manuscript:

We have edited the title and redrafted these discussions in the paper to be more specific.

(2) The scope of the study does not match the ambitions of the introduction. Page 2, Line 31 states: "This effort requires a large amount of data to evaluate against, covering a wide variety of climate and vegetation conditions". Yet within this study only one site is analyzed. The authors might consider better contextualizing the current status of progress towards such a dataset.

We intended this to sentence to make it clear that we did not think that what we present in this paper is a comprehensive evaluation, as it just considers one site. However, we feel that our work can make a worthwhile contribution to a comprehensive evaluation.

Suggested change to manuscript:

We have added a new section ***Can the FIFE dataset make a useful contribution to current-day JULES evaluation and development work?*** to be more explicit about this. This section stresses that lots of datasets need to be considered in land-surface model evaluation and development e.g.

> A global land-surface model such as JULES needs to perform well for a wide range of climate regimes, time scales, spatial scales and vegetation types. Model evaluation or development work needs to represent this variety... When adding a new process to a global land-surface model, it is important to tune new parameters to a comprehensive range of datasets. For example, as mentioned in Section 3.3, Lin et al. (2015) use data for 314 species from 56 sites across the world to tune the new g1 parameter introduced in the Medlyn model of stomatal conductance for key plant functional types. This breadth of sites and vegetation types is essential.

and discusses the contribution that FIFE as a small component of larger evaluation efforts. It also discusses the new concept of 'JULES golden sites', which hopes to facilitate the use of detailed site data in the JULES community:

> although the data is easily downloadable, well documented and in common file formats, is still needs to be manipulated into a format that can be used in JULES runs. We aim to address this issue by providing a suite that can be used to pre-process the FIFE data and run JULES with the configurations described in this manuscript (see the 'code and data availability' section). This aim is central to the provision of this manuscript. FIFE is the first 'JULES golden site', a concept was launched at the annual JULES meeting 2018. A JULES golden site is a site targeted by the JULES community because it can help address one of the key science questions facing JULES and has high-quality observational data that can be used to drive JULES and evaluate the output. It creates a network of researchers within the JULES community with experience of how this site can be exploited for JULES development, with input from site investigators. A key component is the provision of shared runs and evaluation datasets, which can be gradually expanded and improved.

(3) The authors do not acknowledge the mismatch between the leaf level scale and the eddy covariance / ESM gridcells. A short discussion of the challenges of reconciling leaf level parameters with the effective large scale parameters would be merited.

As we mention in the manuscript, the Harper et al 2016 PFT parameters (which we base the global-c4-grass configuration on) have been evaluated both at the site-scale and for global gridded (n96) runs (Harper et al 2016, Harper et al 2018). So these parameters should give relatively good performance at both scales for C4 grass. Since we are our driving our runs with meteorological observations from FIFE and flux tower observations from FIFE, i.e. no gridded datasets, we feel that going into detail about site-scale versus ESM scale is beyond the scope of this study. We do, however, include a brief discussion of the difference between the site-averaged FIFE met product and the met observations at site 4439 in section A1. We discuss the effect of tuning to leaf-level observations on flux-tower scale carbon and water fluxes in section 3.2, where we present the results from the tune-leaf similations.

Suggested change to manuscript:

The new section ***Can the FIFE dataset make a useful contribution to current-day JULES evaluation and development work?*** explicitly says that multiple spatial scales need to be considered in model evaluation:

> A global land-surface model such as JULES needs to perform well for a wide range of climate regimes, time scales, spatial scales and vegetation types.

(4) Observational data record is extremely short (8 days). Are there other data available (remote sensing or flux tower) that could be used to evaluate the different model configurations? Why is only one year of the FIFE data used?

The actual JULES runs were continuous from 1987-05-29 to 1987-10-12 (figure 2). While some datasets were available for longer than the duration of our model runs (e.g. the met forcing was available 1987-9), we were restricted to this length of run by the availability of the LAI observations. Flux measurements were also not taken continuously during the entire the period of our run - just during the Intensive Field Campaigns (IFC), which targeted a critical phase of vegetative development (IFC-1 “greenup", IFC-2 “peak greenness", IFC-3 “dry-down", and IFC-4 “senescence"). We picked the eight days to be representative of each period, and also to coincide with the days analysed in Kim and Verma 1991a, which provides observations.

Suggested change to manuscript:

As part of the new discussion section ***Can the FIFE dataset make a useful contribution to current-day JULES evaluation and development work?*** , we have added:

> There are two main disadvantages to the use of FIFE in evaluation and model development studies. The first is the limited time period: observations are available for a period of up to three years, with some key measurements only undertaken during the intensive field campaigns. Where long term effects are being studied, alternative datasets would need to be used.

(5) Many statements based on literature review are presented without citation in the results and conclusions sections. The relevant citations should be repeated, or the reader should be referred to the specific section where the citations can be found.

Suggested change to manuscript:

Where the new version of the conclusions section refers specifically to a particular study in the literature, we have added in the citation.

P15: Consider moving figure 6 to supplementary

Suggested change to manuscript:

We have moved this figure as suggested and updated the text accordingly.

Figures 8-10: would be interesing to see summary statistics on the goodness of fit for the various parameterizations.

We feel that most of the simpler measures of goodness of fit could be misleading for these particular plots given the shape of the diurnal cycle of GPP, net canopy assimilation and latent heat flux - it would over-emphasize a slight timing offset at the beginning or end of the day, and also influenced by differences between the times of day when observations are available (e.g. observations start at midday on 17th August, and only one observation is available in the crucial 9:30-13:30 period on 11th August).

We have, however calculated R^2 for the fit of the JULES ci:ca ratio to observations, since the model is a straight line, and there are no obvious features of the data which would detract from this interpretation. We use this R^2 to back up our assertion that the two JULES parameters dqcrit and f0 are poorly confined by this dataset (this can also be seen by eye in figure 6, new numbering).

Suggested change to manuscript:

Included R^2 in figure 6 (new numbering) and in the discussion of this figure in the text.

P2.L31: There is a significant disconnect between the first five sentences of this paragraph and the single-site nature of this study.

Suggested change to manuscript:

We have edited the introduction to clarify that we mean this study to contribute towards a larger (multi-site) evaluation effort and added a new section ***Can the FIFE dataset make a useful contribution to current-day JULES evaluation and development work?*** to talk about this issue explicitly.

P17.L24: "Other studies have argued that the dry period diurnal cycle at this site can by captured via an explicit dependence on leaf water potential". I understand this is covered in Section 2.3.2, but I think you should either repeat the citations or refer back to Section 2.3.2.

Suggested change to manuscript:

We have rewritten the conclusion section and this sentence no longer appears. We have looked through the new conclusions for other places where we reference studies in the literature and added the references in (2 occurrences).

P26.L2-3: "JULES is not currently able to capture the diurnal cycle of net canopy photosynthesis at this C4 grass site", unclear which model configuration you are referring to.

Suggested change to manuscript:

This sentence no longer appears in the new version of the conclusions section. We have checked that the new version is explicit about when it is talking about the results from one configuration in particular, and when it is talking about JULES in general.

P26.L2-3: "JULES is not currently able to capture the diurnal cycle of net canopy photosynthesis at this C4 grass site, due to the lack of a strong dependence on the canopy vapour pressure deficit (indirectly or directly)." Second clause needs citation. Not shown within this study.

Suggested change to manuscript:

We have rewritten the conclusions section and this sentence no longer appears in this form. However, there is a sentence in the new conclusions section makes a similar point.

In this new sentence, we say ‘could be addressed’ to emphasise that this is a possible solution (rather than the more definite ‘due to lack of’, which implies it is the only solution):

> This deficiency could be addressed by allowing the effect of soil moisture availability and vapour pressure deficit on stomatal conductance to interact, for example, via leaf water potential.

and we go in to this argument in detail in the new section ***What potential model developments could improve the diurnal cycle of JULES GPP at this site?*** to support this claim.

P26.L4-5: "The temperature response of Vcmax can be tuned to compensate for this, but it is more desirable for the model to respond to high temperature stress and high water stress individually." This is not very well contextualized, perhaps instead you could more specifically say that repro-cox still manages a reasonable diurnal cycle, but likely due to compensating errors, and then refer back to the section where you discuss that in greater detail.

Suggested change to manuscript:

The new conclusions section makes this point with improved clarity and with more context. We have described why it is important for the model to respond to temperature and VPD separately in the new section ***What potential model developments could improve the diurnal cycle of JULES GPP at this site?*** . We have also added plots which show explicitly the effect of using different Vcmax with the repro-cox-1998 runs.

P26.L5-6: "These runs also showed how the default water stress parameterisation can result in large reductions in photosynthesis during periods that are not considered water-limiting at the site." I am not sure which figure you are referring to or which time period specifically.

This sentence referred to section ***Onset of water stress and relationship between water stress and leaf potential*** (from the description of how the tune-leaf configuration is calibrated) but this sentence is no longer in the new version of the conclusions.

Instead, the conclusions section makes the general point that you should not be

> calibrating the unstressed parameters without also checking the time period during which the model considers the vegetation to be unstressed

P26.L10-11: "These have been extensively studied at FIFE in independent investigations and yet still show a wide spread, leading to large modelling uncertainties" needs citation.

This is first described in the ***Experimental set-up*** section but the appendix discusses this in detail, and plots the available observations. The result of uncertainties in LAI, canopy structure, plant-dependent threshold for water stress and critical soil moisture on the canopy water and carbon fluxes is demonstrated in the ***tune-leaf simulations*** part of the results section.

P26.L12: "The FIFE data also indicates ..." How exactly does the FIFE data indicate that JULES should represent leaf rolling and senescence?

We no longer refer to leaf rolling in the new version of the conclusions section.

How can the First ISLSCP Field Experiment contribute to present-day efforts to evaluate water stress in JULESv5.0?~~Revisiting the First ISLSCP Field Experiment to evaluate water stress in JULESv5.0~~

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Abstract. The First ISLSCP Field Experiment (FIFE), Kansas, US, 1987-1989, made important contributions to the understanding of energy and CO_2 exchanges between the land-surface and the atmosphere, which heavily influenced the development of numerical land-surface modelling. Thirty years on, we demonstrate how the wealth of data collected at FIFE and its subsequent in-depth analysis in the literature continues to be a valuable resource for the current generation of land-surface models. To illustrate, we use the FIFE dataset to evaluate the representation of water stress on tallgrass prairie vegetation in the Joint UK Land Environment Simulator (JULES) and highlight areas for future development. We show that, while JULES is able to simulate a decrease in net carbon assimilation and evapotranspiration during a dry spell, the shape of the diurnal cycle is not well captured. Evaluating the model parameters and results against this dataset provides a case study on the assumptions in calibrating 'unstressed' vegetation parameters and thresholds for water stress. In particular, the response to low water availability and high temperatures are calibrated separately. We also illustrate the effect of inherent uncertainties in key observables, such as leaf area index, soil moisture and soil properties. Given these valuable lessons, simulations for this site will be a key addition to a compilation of simulations covering a wide range of vegetation types and climate regimes, which will be used to improve the way that water stress is represented within JULES.

1 Introduction

Models of the land surface and biosphere, a key component in climate predictions and projections, depend on high quality observational datasets ~~data sets~~ to tune the behaviour of the modelled processes. A significant contribution in this field was produced by the First ISLCP[1] Field Experiment (FIFE), an interdisciplinary collaboration of researchers from remote sensing, atmospheric physics, meteorology and biology. It was based at and around the Konza Prairie Long Term Ecological Research (LTER) site, Kansas, during multiple campaigns, 1987-1989. Its principal objectives were twofold: to improve the understanding of the role of biological processes in controlling atmosphere–surface exchange of heat, water vapour and CO_2, and to investigate whether satellite observations can ~~could be used to~~ constrain land surface parameters relevant to the climate system (Sellers et al., 1988; Sellers and Hall, 1992).

As part of this experiment, canopy processes were related to leaf-level stomatal conductance, photosynthesis and respiration, including detailed modelling of ~~and~~ responses to water availability and atmospheric forcing~~were modelled in detail~~ (Verma et al., 1989; Kim and Verma, 1990b, a, 1991a, b; Verma et al., 1992; Kim et al., 1992; Stewart and Verma, 1992; Norman et al., 1992; Niyogi and Raman, 1997; Cox et al., 1998; Colello et al., 1998). This work has subsequently played an important role in influencing the representation of vegetation in a generation of land-surface models. The parametrisation of water stress in the the Joint UK Land Environment Simulator (JULES) (Best et al., 2011; Clark et al., 2011), for example, originates in a canopy conductance and photosynthesis model presented in Cox et al. (1998), which was developed using FIFE observations. After tuning, the Cox et al. (1998) model gave a very good fit to the data: it explained 91.7% of the variance in net canopy photosynthesis and 89.4% of the variance in canopy conductance, as derived from FIFE flux tower observations. As part of this model, Cox et al. (1998) calculated a piecewise-linear stress factor β. This factor is zero below the wilting soil moisture and one above a critical soil moisture (Figure 1, solid line), based on the top 1.4m of soil. Crucially, Cox et al. (1998) found that the drop in carbon assimilation in the C4 vegetation as soil water content decreased at FIFE could only be reproduced if the stress factor β was applied directly to the net leaf assimilation rate. In their model, soil water stress affected stomatal conductance via the net leaf assimilation rate.

The Cox et al. (1998) stress parameterisation was adopted in early versions of JULES. It was the only implementation of soil moisture stress in JULES until version 4.6 and, to our knowledge, has been used in all published studies to date. The JULES wilting and critical soil moistures are input by users for each soil layer in each gridbox, and are defined as corresponding to absolute matric water potentials of 1.5 MPa and 0.033 MPa respectively (Best et al., 2011). A separate stress factor is calculated for each soil layer, and these are combined into an overall soil moisture stress factor by weighting by the root mass distribution. Other options have been more recently implemented into JULES. These include a ‘bucket’ approach, in which the stress factor β is calculated from the average soil moisture to a specified depth, and the introduction of a new variable p_0 which reduces the soil moisture at which a vegetation type first starts to experience water stress (Figure 1, dashed line).

There is currently a community-wide effort to improve the response of JULES to drought conditions. This effort requires a large amount of data to evaluate against, covering a wide variety of climates and vegetation types, in order to give confidence

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[1] International Satellite Land Surface Climatology Project

Figure 1. JULES soil moisture stress factor β with p_0=0 (solid line) and p_0=0.3 (dashed line). The soil moisture threshold at which the plant becomes completely unstressed ($\beta = 1$) is $\theta_{wilt} + (\theta_{crit} - \theta_{wilt})(1 - p_0)$.

in the underlying representation of this process in the model~~climate and vegetation conditions. This will ensure that any improvements have global applicability, rather than being effective only for a small subset of sites~~. This is vital if the model is to be used to simulate global responses to changes in water availability in the future.

Observations taken during the FIFE campaign are still available today, through the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL-DAAC). Given that FIFE observations were ~~important for generating worldwide predictions of responses to any changing futuredrought conditions. The FIFE data is well documented, easily available and was~~ fundamental to the development of the original water stress parametrisation in JULES, we revisit this dataset to determine whether it would make a useful contribution to present-day efforts to improve this process. We aim to demonstrate that there is sufficient data available, and of a sufficient quality, to show that the current version of JULES is unable to capture key features of the impact of water availability on the temperate grassland vegetation at the FIFE site. This can provide a benchmark for this vegetation type, against which future model developments can be assessed. We thus hope to encourage the inclusion of this dataset in comprehensive, multi-site studies that aim to improve the representation of this process on a global scale.

We proceed ~~. Hence we revisit its use in the next stage of development of water stress in JULES. We do this~~ as follows. We first create a simulation that closely reproduces the Cox et al. (1998) study, in order to investigate how this original study was able to provide such a close fit to the observed carbon and water fluxes at FIFE. Our second configuration uses ~~. Secondly, we update this configuration to make use of~~ more recent model developments, with parameter values based on the generic C4 grass tile from the global analysis of Harper et al. (2016). These settings are typical for how this vegetation type is usually represented in current-day runs of JULES. We then use FIFE observations to tune some of these generic C4 grass parameters to more accurately represent tallgrass prairie. The aim here is to allow us to distinguish between model limitations due to approximating this specific vegetation type by generic C4 grass parameters and model limitations due to missing or inadequately represented processes within the model. The model ~~model~~ setup for each of these simulations is described in Section 2. In Section 3, we compare the results from the model simulations to net canopy carbon assimilation, derived from CO_2 flux measurements, and latent heat energy flux measurements at the FIFE site. We conclude ~~in~~ with a summary of what lessons ~~the lessons that~~ can be learnt for improving water stress in JULES from FIFE and how this dataset can be useful to the JULES community into the future. Throughout, we refer to the appendices, which give more information about the use of the observations and the alternative datasets considered, in order to assist future modelling work at this site, both with JULES and other land-surface models. A important component of this study is the provision of a complete JULES setup that can be downloaded and used to run FIFE data through the JULES model, to allow easy inclusion of this site into a comprehensive evaluation framework for JULES.

2 Experimental set-up

We will focus on ~~use~~ three different configurations of JULES:

- Simulation 1: `repro-cox-1998`. A simplified JULES run which reproduces the original Cox et al. (1998) study as closely as possible. This requires the simple 'big leaf' canopy scheme, prescribes the Leaf Area Index (LAI) and soil moisture from observations, and calculates the soil moisture stress from the average soil moisture in the top 1.4m of soil.
- Simulation 2: `global-C4-grass`. This run uses parameter settings from Harper et al. (2016), which has a generic representation of C4 grass. It uses many of the 'state-of-art' features of JULES, such as the layered canopy scheme with sunflecks, and calculates soil moisture stress using a weighted sum of the stress factors ~~factor~~ in each soil layer. LAI and soil moisture are prescribed.
- Simulation 3: `tune-leaf`. As above, but we investigate whether the generic C4 grass leaf parameters can be tuned to site measurements, to give a more accurate representation of the prairie vegetation.

These configurations are described below and summarised in Table 1. All the FIFE datasets used in this study are given in Table 2.

2.1 Simulation 1: `repro-cox-1998`

Our first simulation, `repro-cox-1998`, closely reproduces the optimal configuration presented in the Cox et al. (1998) study. Cox et al. (1998) modelled the fluxes for FIFE site 4439 (situated at 39° 03' N, 96° 32' W, 445 m above mean sea level). This tallgrass prairie site is roughly central within the 15km × 15km FIFE study area. It had been lightly grazed by domestic livestock, but was ungrazed in 1986 and 1987 and was burned on 16th April 1987 (Kim and Verma, 1990a, 1991b). At the flowering stage in 1987, more than 80% of the vegetation was composed of C4 grasses (Kim and Verma, 1990a).

For their analysis, Cox et al. (1998) selected daylight hours that were both after 10 am local time, to exclude dew evaporation, and from days with no rainfall during that day or the preceding day. This minimised the effect of evaporation of rainfall from the canopy and soil surface and let them focus on modelling transpiration and net canopy assimilation. We will also restrict our analysis to these same time periods. The model was spun up by repeating the entire run ten times, and the output from the eleventh run was analysed.

For driving data, we use a site-averaged product of the FIFE Portable Automatic Meteorological Station (AMS) data at 30 minute resolution (Betts and Ball, 1998). We prescribe both LAI and soil moisture from observations (Stewart and Verma, 1992) rather than calculating these variables internally using the JULES phenology or soil hydrology schemes. We use a 'bucket approach' to calculate the soil moisture stress factor from the average soil moisture in the top 1.4m (this option has been available from JULES 4.6 onwards), again to mimic the Cox et al. (1998) analysis. The wilting soil moisture θ_{wilt} was set to 0.205 m^3 m^{-3} and the critical soil moisture θ_{crit} was set to 0.387 m^3 m^{-3}, taken directly from Cox et al. (1998). The resulting stress factor is plotted in Figure 2, and clearly shows the dry period during late July and early August.

Figure 2. Daily mean soil moisture stress factor β for each JULES simulation at FIFE site 4439 in 1987.

JULES and the Cox et al. (1998) optimal configuration both use the Collatz et al. (1992) C4 photosynthesis scheme. They also both use the same stomatal conductance parametrisation: Jacobs (1994), which is in turn a simplified version of the Leuning (1995) scheme. We select the 'big leaf' option from the available canopy schemes in JULES, again to mimic Cox et al. (1998).

In this way, we are able to closely reproduce the Cox et al. (1998) calculation of daytime net canopy carbon assimilation and daytime canopy conductance with a modern version of JULES. Any remaining differences are minor. For example, in Cox et al. (1998) leaf temperature is calculated from the air temperature and observed sensible heat flux whereas, in JULES, the full energy balance is modelled. There are also differences in the calculation of evaporation from soil and canopy, which are not the focus of this study. The calculation of aerodynamic resistance also differs. For example, in this run, canopy height is prescribed using the data from Verma et al. (1992) for this site in 1987 (see Section 5.5 for more information), whereas it was not modelled explicitly as part of the Cox et al. (1998) analysis.

Many of the key FIFE datasets used in this run have large uncertainties, despite being comprehesively measured by multiple teams. LAI measurements have an error of approximately 75% due to the inherent variability of prairie vegetation. LAI measurements are also affected by leaf curling or folding as the leaves pass through the detector. There are therefore significant differences between datasets (for a more detailed description, see Section 5.2). For example, at the beginning of August, LAI measurements vary from 2.5 (Stewart and Verma, 1992) to 0.7 (the FIFE_VEG_BIOP_135 dataset). Soil moisture was also comprehensively measured across the FIFE area by multiple groups (see Section 5.3). While these observations are qualitatively consistent, one of the datasets shows a bias in the lower soil levels at site 4439 in 1987 compared to the other datasets. Within-site variability in soil moisture is also large. Soil properties were similarly well studied: there are four different datasets which can be used to calculate the wilting and critical soil moistures, plus the values from two additional published studies (described in Section 5.4). However, measurements differ from each other by more than 0.15 $\mathrm{m^3\ m^{-3}}$ in some cases. There also appears ~~appear~~ to be differences between layers, with the top 10 cm having consistently lower wilting and critical thresholds than soil at a depth of about 30 cm, for example. It is therefore vital that we consider the implications of the spread in observed LAI, soil moisture and soil properties at this ~~well studied~~ site when drawing our conclusions.

2.2 Simulation 2: `global-C4-grass`

In our second simulation, we use a recent JULES configuration, presented in Harper et al. (2016). This study introduced a trait-based approach to calculating leaf physiology in JULES, and tuned plant parameters to observations in the TRY database (Kattge et al., 2011). Global vegetation was split into 9 plant functional types (PFTs), including one to represent all C4 grasses. The developments introduced in Harper et al. (2016) ~~This~~ resulted in improved site-scale and global simulations of plant productivity and global vegetation distributions (Harper et al., 2018). Our `global-C4-grass` configuration is based on the representation of C4 grasses in Harper et al. (2016) and ~~. This configuration~~ takes advantage of many of the modern features of JULES. This includes a layered canopy scheme that treats the direct and diffuse components of the incident radiation separately (as in Sellers (1985)) and includes sunflecks (Dai et al., 2004; Mercado et al., 2007, 2009). It also calculates the overall soil moisture stress factor β from the sum of the stress factors ~~factor~~ in each layer, weighted by the root mass distribution. Since we are focussing specifically on the parameterisation of water stress, we continue to prescribe LAI and soil moisture, rather than calculate these parameters dynamically with the JULES phenology and soil hydrology schemes.

The driving data was taken from the site-averaged Betts and Ball (1998) product. The diffuse radiation fraction was calculated from shortwave radiation using the method in Weiss and Norman (1985) (see Section 5.1 for more information). A spherical leaf angle distribution was used, as in Harper et al. (2016). LAI was prescribed using the Stewart and Verma (1992) observations and the vegetation was set to generic C4 grass.

The Stewart and Verma (1992) soil moisture observations were partitioned into the four JULES soil layers (thicknesses 0.1m, 0.25m, 0.75m and 2.0m) using an offline version of the soil hydrology scheme in JULES, assuming the same root distribution as natural C4 grass in Harper et al. (2016). This is described in more detail in Section 5.3.1. The wilting and critical volumetric soil moistures and the soil albedo were set to the same values as the `repro-cox-1998` run. As Figure 2 shows, the resulting soil moisture stress factor is almost identical to the simulation `repro-cox-1998`. Canopy height was also prescribed using the same observations as the `repro-cox-1998` configuration, and the run was initialised from the spun up `repro-cox-1998` run.

2.3 Simulation 3: `tune-leaf`

For the third configuration, `tune-leaf`, we calibrate the JULES parameters to measurements of the tallgrass prairie vegetation at this particular site. At the flowering stage in 1987, the vegetation at FIFE site 4439 was dominated by three C4 grass species: 27.1% *Andropogon gerardii* (Big bluestem), 22.2% *Sorghastrum nutans* (Indiangrass) and 16.6 % *Panicum virgatum* (Switchgrass) (Kim and Verma, 1990a). Since individual LAI observations for each species (as used in e.g. Kim and Verma (1991b)) were not available, we continue to model this site with a single plant tile. We tune the leaf parameters of this tile to be approximately representative of the dominant species at this site, *A. gerardii*.

2.3.1 Leaf properties prior to the application of water stress in the model

As discussed above, JULES uses the Collatz et al. (1992) C4 photosynthesis scheme to calculate the unstressed net leaf photosynthetic carbon uptake and the Jacobs (1994) relation to calculate stomatal conductance. In this section, we calibrate these parameterisations to the available *in situ* observations. A brief description of each of the model parameters fitted in this section is given in Table 3, and they are defined in full in Clark et al. (2011) and Best et al. (2011). Throughout ~~For the purposes of~~ this calibration work, the model points/lines are calculated ~~JULES parameterisations have been reproduced~~ with the Leaf Simulator package (Williams et al., in prep). This package exactly reproduces the way that JULES calculates leaf carbon uptake and stomatal conductance, but allows leaf-level observations to be used as input.

Knapp (1985) compared leaf-level measurements of *A. gerardii* and *P. virgatum* in burned and unburned ungrazed plots on the Konza Prairie Research Natural Area in 1983, and the response of these two species to different water stress conditions. Their plots were located at 39° 05’ N, 96° 35’ W, which is within what subsequently became the FIFE study area. The burning occurred in April 1983, to prior to initiation of growth of the warm-season grasses. They found significant differences between vegetation in the burned plot and unburned plots during the May to September period. The particular FIFE site we are modelling in our simulations, site 4439, was also burned prior to the start of the experiment (15th April 1987, Kim and Verma (1990a)), and was ungrazed throughout the FIFE period. Therefore, we use the observations from the burned plot in Knapp (1985) during May-June 1983, when they describe water availability as ~~water was~~ ‘not limiting’ (we will investigate this claim in more detail in Section 2.3.2), to constrain our unstressed leaf photosynthesis parameters in the `tune-leaf` configuration. First, we set specific leaf area and the ratio of leaf nitrogen to leaf dry mass for *A. gerardii* and *P. virgatum* to Knapp (1985) observations taken between 25th May and 10th June 1983. Once these parameters are fixed, we then fit the other parameters in the model light response curve by comparison with the light curve presented in Knapp (1985), which was compiled from observations taken May-June 1983 at 35±2°C (Figure 3).

Knapp (1985) also investigated the temperature dependence of net leaf photosynthesis by artificially altering the temperature of leaves of *A. gerardii* and *P. virgatum*. Their observations showed that the peaks in both species occurred at approximately the same temperatures, but that the peak was significantly broader in *A. gerardii* than *P. virgatum*. In JULES, the temperature dependence of net leaf assimilation for C4 plants is introduced through a temperature-dependent parameterisation of the maximum rate of carboxylation of Rubisco V_{cmax}. This enters the calculation of both the gross rate of photosynthesis and the dark leaf respiration R_d (since model R_d is proportional to model V_{cmax}). Therefore, we can use the relation between net leaf assimilation and temperature presented in Knapp (1985) to calibrate the JULES parameters governing the temperature dependence of V_{cmax} in the model. The result is illustrated in Figure 4, alongside the parametrisations used in the `repro-cox-1998` and `global-C4-grass` runs. The lines calibrated to the Knapp (1985) observations peak at approximately 38°C, whereas the `repro-cox-1998` and `global-C4-grass` parameterisations peak at approximately 32°C and 41°C respectively. This leads to very different model behaviour in the temperature range 32-42°C, where the `repro-cox-1998` parameterisation shows a dramatic decline in V_{cmax}, which contrasts sharply with the increase shown in the `global-C4-grass` parameterisation and the more stable lines calibrated to the Knapp (1985) observations. Note also that Polley et al. (1992) found ‘no apparent relationship’ between leaf temperature and net leaf carbon assimilation in measurements of *A. gerardii*, *S. nutans* and *P. virgatum*, taken at ambient temperatures between 24.1°C and 47.8°C. They speculate that the difference between their results and the temperature relations found by Knapp (1985) is due to seasonal acclimatisation.

As already stated, for ~~For~~ the `tune-leaf` configuration, we use JULES parameters fit to the *A. gerardii* data from Knapp (1985), since *A. geradii*~~*gerardii*~~ is the dominant species at this site. However, to investigate the uncertainty introduced by the variation between species, we repeat the runs using parameters fitted to the approximate midpoint of *A. gerardii* and *P. virgatum* light response curves and V_{cmax} temperature relations. We would expect that the best parameter set to lie between these two parameterisations. However, note that Knapp (1985) does not have data for *Sorghastrum nutans*, the second-most dominant plant species at FIFE site 4439, so we were not able to take this species into account in this part of the calibration.

It should also be noted that Knapp (1985) reported a drop in the ratio of leaf nitrogen to leaf dry mass over the course of the 1982 season of more than 50% in the burned plots. This could be a contributing factor to the drop in leaf assimilation they observed over the course of 1983. We were not able to incorporate a time-varying ratio of leaf nitrogen to leaf dry mass into our simulations, which could lead to an overestimation of leaf assimilation in the senescence period.

There were also gas exchange measurements on individual leaves of *A. gerardii*, *S. nutans* and *P. virgatum* taken as part of the FIFE intensive field campaigns in 1987 (Polley et al., 1992). These observations were taken on upper canopy leaves perpendicular to the direct beam of the Sun, with varying absorbed PAR and internal CO$_2$ concentrations (FIFE_PHO_LEAF_46). This includes observations taken before, during and after the dry spell. Therefore, if we are to use these observations to calibrate the unstressed model parameters, we have to process them in such as way as to minimise the influence of the parameterisation of water stress in the model~~water stress~~.

To achieve this, we identified individual net leaf assimilation (A_l) versus leaf internal CO$_2$ concentration (c_i) curves from the FIFE_PHO_LEAF_46 dataset for *A. gerardii* and *P. virgatum* (using the observation time and leaf area). We normalised each A_l-c_i curve using the mean A_l for $c_i > 150\mu$ mol CO$_2$ (mol air)$^{-1}$ for that curve~~at high c_i~~. We then selected A_l-c_i curves with mean incident radiation greater than 1200 μmol PAR m^{-2} s^{-1}. This procedure minimises the dependence on water stress or individual leaf nitrogen levels, since these factors approximately cancel out in the relations used internally in JULES when they are manipulated in this way. We can then use these normalised curves to calibrate the model A_l-c_i response at low c_i. For *A. gerardii* and, to a lesser extent, *P. virgatum*, this leads to a decrease in the initial slope of the A_l-c_i curve (Figure 5).

We also attempted to use the A_l-c_i curves identified in the FIFE_PHO_LEAF_46 dataset to calibrate the parameters in the JULES relationship between internal leaf CO$_2$ concentration and external CO$_2$ concentration c_a ~~c_i-c_a relationship~~. Each individual A_l-c_i curve was taken at approximately constant humidity, and c_a is also provided for each point on the curve~~a constant humidity~~. JULES uses the Jacobs (1994) parameterisation

$$\frac{c_i - \Gamma}{c_a - \Gamma} = f_0 \left(1 - \frac{dq}{dq_{crit}}\right), \tag{1}$$

where Γ is the photorespiration compensation point ($\Gamma = 0$ for C4), dq is specific humidity deficit at the leaf surface. f_0 and dq_{crit} are plant-dependent parameters: f_0 is a scaling factor on c_i and dq_{crit} governs the strength of humidity dependence of c_i. This parameterisation predicts that plotting c_i against c_a at constant humidity would give a straight line, with gradient $f_0 \left(1 - \frac{dq}{dq_{crit}}\right)$. However, when plotting observations from FIFE
SUBSCRIPTNBPHO
SUBSCRIPTNBLEAF
SUBSCRIPTNB46, we found ~~plotting c_i against c_a implied~~ that the slope of the c_i-c_a relationship changed ~~changes~~ as c_a increased (see ~~increases (~~Figure S8 in the supplementary material). Therefore, we were ~~are~~ unable to calibrate the JULES c_i-c_a relationship to this data.

Instead, we use leaf measurements of C4 grass in the Konza prairie, collected in 2008 and published as part of Lin et al. (2015). These were taken at ambient CO_2 levels, under unstressed conditions. We can derive the c_i/c_a ratio from the supplied stomatal conductance, net assimilation and internal CO_2 observations, and plot this against specific humidity deficit at the leaf surface, calculated from chamber VPD, neglecting the effect of the leaf boundary layer (Figure 6). We calibrate the Jacobs model parameters f_0 and ~~keep~~ dq_{crit} to this data (green solid line). Given the large scatter of the data and resulting poor fit (R^2=0.04), we will also explore the effect of varying dq_{crit} (green dashed lines a,b,c). In each case, f_0 is set to best fit this dataset for this dq_{crit} (the parameter values are given in Table 4).

~~at the same value as the configuration.~~ Both Knapp (1985) and Polley et al. (1992) found that leaf stomatal conductance g_s is proportional to the net leaf assimilation at this site. Their results are approximately consistent with the Lin et al. (2015) observations, given the difference in ambient CO_2 levels and the weak dependence on VPD~~We therefore set f_0 using the gradient of the relationship between net leaf assimilation and g_s fitted in to their leaf observations, assuming $dq = 0.02$ (mean of the ambient FIFESUBSCRIPTNBPHOSUBSCRIPTNBLEAFSUBSCRIPTNB46 measurements). We will investigate the effect that other values of dq_{crit} would have on our results in~~.

As discussed above, in JULES, ~~JULES~~ dark leaf respiration R_d is calculated from model V_{cmax}, scaled by a constant. For the `tune-leaf` simulation, we tune this constant such that the model dark leaf respiration at 30°C matches the dark leaf respiration from Polley et al. (1992) at 30°C (Figure 7). This is roughly double the dark leaf respiration at 30°C in the `repro-cox-1998` and `global-C4-grass` configurations. The Polley et al. (1992) relation was fitted to observations made at leaf temperatures of approximately 14-46°C. While our tuned model parameterisation of dark leaf respiration compares reasonably well in the range 25-35°C, it rapidly diverges from the Polley et al. (1992) observations beyond this range. This is particularly true for the higher temperature values, where the observations in Polley et al. (1992) show an increase with temperature, whereas the `tune-leaf` JULES configuration shows a decrease.

Polley et al. (1992) found no significant difference between *A. gerardii*, *S. nutans* and *P. virgatum* for a variety of leaf properties: net leaf assimilation under ambient conditions, maximum assimilation under high light and CO_2 saturation, temperature response of net assimilation and relationship between assimilation and stomatal conductance under ambient conditions. This implies that the uncertainty we have introduced by not considering *S. nutans* data throughout most of this calibration is relatively minor. ~~also found that there was ‘no apparent relationship’ between leaf temperature and net leaf carbon assimilation in their measurements of A. gerardii, S. nutansand P. virgatum, taken at ambient temperatures between 24.1and 47.8. They speculate that the difference between their results and the temperature relations found by is due to seasonal acclimatisation. On the one hand, this supports the change from using the rapidly varying V_{cmax} with temperature in this regime in both the and simulations to using the relatively more stable parameterisation. On the other hand, it implies that an even more stable parameterisation would be desirable. We will revisit this issue in .~~

2.3.2 Onset of water stress and relationship between water stress and leaf water potential

In this section, we calibrate the parameter governing the onset of soil water stress in the model, p_0. In the `repro-cox-1998` and `global-C4-grass` simulations, p_0 is set to 1, meaning that the model vegetation starts to experience soil water stress at a volumetric soil moisture $\theta=\theta_{crit}$=0.387 m^3 m^{-3} (Figure 1). This leads to a soil moisture stress factor β of 0.75-0.55 during the first 10 days of June 1987, i.e. a reduction of 25-45% compared to the case where model vegetation is not limited by water availability (Figure 2).

We can investigate this in more detail using leaf water potential observations as an indicator of the stress levels of the vegetation. Leaf water potential is affected by both the soil water content and the atmospheric water content, as well as other factors affecting transpiration. Both Polley et al. (1992) and Knapp (1985) found a relationship between leaf water potential and net leaf assimilation in their measurements of grasses in the FIFE study area. Polley et al. (1992) measured leaves of *A. gerardii* and *S. nutans* throughout the 1988 growing season. These observations showed a drop in net leaf carbon assimilation as the leaf water potential declined through the season: leaf water potentials -0.34 to -1.5 MPa were consistent with net leaf carbon assimilate rates of 16.2 to 41.5 μmol m^2 s^{-1} whereas lower leaf water potentials of -1.5 to -2.45MPa were consistent with lower rates of 3.9 to 15.5 μmol m^2 s^{-1} (at internal CO_2 concentrations of 200 μmol mol^{-1} and absorbed PAR of 1600 μmol absorbed quanta m^2 s^{-1})). Knapp (1985) carried out weekly leaf water potential measurements of *A. gerardii* and *P. virgatum* in 1983 for late May to early October, which showed midday leaf water potential dropping from -0.4MPa in late May to less than -6.6MPa (the pressure chamber limit) at the end of July. During this period, net leaf assimilation dropped from approximately 40μmol m^2 s^{-1} to less than 10μmol m^2 s^{-1}.

Kim and Verma (1991b) proposed a model which considers the prairie vegetation to be completely unstressed until the leaf water potential drops below -1 MPa. This was partially motivated by the Polley et al. (1992) measurements and evaluated using observations of FIFE site 4439 in 1987, i.e. the same site and time period we use in this study. Kim and Verma (1991a) proposed an alternative water stress model, also based on data in Polley et al. (1992), where both the maximum rate of carboxylation of Rubisco V_{cmax} and the maximum rate of carboxylation allowed by electron transport J_{max} had a dependence on leaf water potential. According to this parameterisation, a leaf water potential of -0.4 MPa introduces a factor of 0.97 into V_{cmax}, for example, and a leaf water potential of -0.8 MPa introduces a factor of 0.91.

Midday leaf water potential for *A. gerardii* in the burned plot was approximately -0.4 MPa during the Knapp (1985) ~~their~~ ‘early season’ measurement period. Therefore, according to both the Kim and Verma (1991b) and Kim and Verma (1991a) models, considering this period ‘unstressed’ is a very good approximation (i.e. $\beta = 1$, to within 3%), and agrees with their statement that "water was not limiting" the vegetation during this period. This validates our use of the Knapp (1985) ~~this~~ data set to tune the ’unstressed’ JULES parameters in the previous section.

We can now use the same arguments to determine how much water stress the vegetation should be experiencing at the beginning of June in our runs at FIFE site 4439 in 1987. Kim and Verma (1991a) present hourly leaf water potential measurements for *A. gerardii* leaves at this site, for a selection of days in 1987 (Figure 8). ~~1987.~~ On 5th June 1987, they measured a minimum leaf water potential of approximately -0.8 MPa at 2pm local time. According to the Kim and Verma (1991b) model, vegetation at this leaf water potential would not be water stressed, and according the Kim and Verma (1991a) model, V_{cmax} would be reduced by approximately 9%. This contrasts sharply with the reduction in net assimilation throughout the day of 39%, due to water stress (i.e. $\beta = 0.61$), experienced in both the `repro-cox-1998` and `global-C4-grass` simulations on this day.

For the `tune-leaf` configuration, we therefore reduce the early season water stress, to be more consistent with Kim and Verma (1991a) and Kim and Verma (1991b). This can be achieved by introducing a non-zero p_0 value in the stress factor β. This reduces the soil moisture threshold at which the plant becomes completely unstressed ($\beta = 1$) from θ_{crit} to $\theta_{wilt} + (\theta_{crit} - \theta_{wilt})(1 - p_0)$, as illustrated in Figure 1. Assuming that the stress factor β is 0.9 on 5th June 1987 leads to p_0=0.3. The effect of different values of p_0 will be shown in more detail in Section 3.

We now examine whether any previous modelling studies at this site support or conflict with this reduction in the soil moisture threshold at which the plant becomes completely unstressed. Crucially, the maximum soil moisture stress factor considered in the original Cox et al. (1998) study was 0.7, therefore a setup with a p_0 of 1-0.7=0.3 and parameters re-tuned to give a 30 % reduction in unstressed net leaf assimilation, would have given the same fit to the data. Similarly, a stress function with p_0=0.3 fits the plot of the ratio of actual to potential evapotranspiration to available water in Verma et al. (1992) (when corrected for their different soil properties) at least as well as a stress function with p_0=0. An increase in p_0 can also be considered a proxy for decreasing θ_{crit} (which, as we have already noted, has a large uncertainty: see Section 5.4). A p_0 of 0.2, for example, can be used to mimic the impact of changing θ_{crit} from 0.387, as used in this study and in Cox et al. (1998), to 0.348, as used in Verma et al. (1992).

Kim and Verma (1991a) present hourly water potential measurement of *A. gerardii* leaves at FIFE site 4439 for 3 other days (in addition to 5th June 1987): 2nd July (peak growth period), 30th July (dry period), 20th August 1987 (early senescence). These show a minimum of -1.2MPa, -2.6MPa and -1.7MPa respectively (Figure 8). Given the relationships between leaf water potential and net leaf assimilation described above, these leaf water potential measurements imply a drop in leaf assimilation during the middle of day in the dry period. In contrast, Polley et al. (1992) found ‘no evident seasonal trend’ in the maximum leaf assimilation rate or carboxylation efficiency, despite taking observations throughout the day before, during and after the dry spell in 1987[2]. We were unable to reconcile these results satisfactorily using the associated data in the FIFE SUBSCRIPTNBPHO SUBSCRIPTNBLEAF SUBSCRIPTNB46 dataset (chamber vapour pressure, leaf and chamber CO_2 concentrations, leaf and chamber temperatures). ~~The apparent lack of water stress in these measurements can be reconciled if the vapour pressure deficit (VPD) in the gas chamber for measurements taken during the hottest part of the day in the dry period is less than in the ambient air, which would raise the leaf water potential for leaves in the chamber compared to ambient leaves. The diurnal cycle in the leaf water potential measurements on 30th July in also shows the strong influence of the atmospheric VPD. As we will see, the effect of water stress on C4 photosynthesis in JULES is almost entirely driven by the drop in soil moisture in the root zone (parameterised by β) and the influence of VPD is negligible (since it enters via c_i, as described in). This will limit the ability of JULES to capture diurnal variations in water stress on leaf carbon assimilation.~~

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[2] Tim Arkebauer, personal communication, and timestamps from the FIFE_PHO_LEAF_46 dataset

2.3.3 Canopy and optical properties

For the `tune-leaf` configuration, we keep the values of leaf reflectance and transmittance from `global-C4-grass`, as they are consistent with those measured by Walter-Shea et al. (1992) in 1988 and 1989 as part of the FIFE experiment. Walter-Shea et al. (1992) found that leaf optical properties were not dependent on leaf water potential in the range -0.5 to -3.0 MPa. Leaf angle distribution measurements were taken as part of the FIFE campaign (SE-590_Leaf_Data), and tended towards erectophile (Privette, 1996). However, erectophile leaf angle distributions can not currently be set in JULES, so we continue to use a spherical angle distribution, as in the `global-C4-grass` run. Walter-Shea et al. (1992) noted that the leaf angle distribution of grass at FIFE site 4439 was affected by water availability: they concluded that severe water stress in 1988 probably contributed to a more vertical leaf orientation in 1988 than in 1989. The uniformity of the canopy in JULES can be parameterised by a canopy structure factor a ($a = 1$ indicates a completely uniform canopy, $a < 1$ indicates clumping). It is difficult to get a numerical estimate of how uniform the canopy is at FIFE site 4439 because of the large uncertainties in LAI measurements, which we discuss in Section 5.2. However, using LAI from Stewart and Verma (1992), together with FIFE observations of the fraction of absorbed photosynthetically active radiation (LB_UNL_42) on a day with mostly diffuse radiation (7th August 1987), gives a rough estimate for a canopy structure factor of 0.8. The structure factor changes the effective LAI seen by the model radiation scheme, and so can be used to investigate the effects of the uncertainty in the LAI dataset.

Leaves of *A. gerardii* roll (fold) in response to water stress, which reduces their sunlit area while still allowing photosynthesis to continue (Knapp, 1985). This dynamic response of the leaves to drought conditions could be an important factor in modelling canopy photosynthesis during dry spells. However, this behaviour is not implemented ~~cannot be modelled~~ in the current version of JULES.

2.3.4 Summary of `tune-leaf` configuration

The `tune-leaf` configuration contains parameters that are, in theory, more appropriate to the ~~improves the representation of the~~ tallgrass prairie vegetation at this site, by tuning the underlying model processes ~~by tuning~~ to leaf and canopy measurements taken in the FIFE study area. The response of leaf photosynthesis to light, CO_2 and, particularly, temperature have been fitted to observations. We note that previous studies have indicated a relationship between leaf water potential and net leaf assimilation observations at this site, and that leaf water potential can be considered an indication of the water stress that the vegetation is experiencing. While JULES does not model leaf water potential explicitly, a review of the available leaf water potential observations measurements indicates the ~~has been improved. Leaf water potential observations indicate the~~ need to delay the onset of model water stress in this tuned configuration~~our run~~, compared to the `repro-cox-1998` and `global-C4-grass` configurations, which we achieve through setting a non-zero p_0 parameter~~. These observations also indicate an influence of VPD on C4 photosynthesis during periods of low soil moisture, which is not captured by the model~~. We note that there remains significant uncertainty in the threshold for the onset of water stress, the calculation of internal CO_2 concentration and the uniformity of the canopy. There is also an uncertainty introduced by inter-species variation. We note that the comparison with observations has revealed some possible limitations of the model, such as the fixed leaf nitrogen content and leaf orientation (spherical) through the season and an absence of leaf folding.

Figure 3. Mean observations from Figure 1 in Knapp (1985) from the burned plot, early season (May-June 1983) for *A. gerardii* (cyan diagonal crosses) and *P. virgatum.* (yellow vertical crosses) for net CO_2 assimilation rate against incident PAR, at 35±2°C . JULES parameters are fitted to the *A. gerardii* observations (cyan dashed line), *P. virgatum.* (yellow dashed line) and a combination of both (green solid line). Also shown are the relations from the `repro-cox-1998` (red dotted line) and `global-C4-grass` runs (blue dot-dashed line), at 35°C . Fitted lines assume no water stress (i.e. $\beta = 1$) and c_i=200 μ mol CO_2 (mol air)$^{-1}$. Model lines have been created using the Leaf Simulator package, which reproduces the internal JULES calculations.

Figure 4. V_{cmax} against leaf temperature for *A. gerardii* (cyan diagonal crosses) and *P. virgatum.* (yellow vertical crosses), using the normalised observations from Figure 2 in Knapp (1985), scaled using the fitted light response curves of *A. gerardii* and *P. virgatum* at 35°C shown in Figure 3. JULES parameters are fitted to these derived *A. gerardii* observations (cyan dashed line) and *P. virgatum.* observations (yellow dashed line) and a combination of both (green solid line). Also shown are the relations from the `repro-cox-1998` (red dotted line) and `global-C4-grass` runs (blue dot-dashed line). Model lines have been created using the Leaf Simulator package.

Figure 5. Black crosses: A_l-c_i curves for *Andropogon gerardii* (left) and *Panicum virgatum* (right) from FIFE_PHO_LEAF_46 (Polley et al., 1992), normalised by the mean A_l of the data points with $c_i > 150\mu$ mol CO_2 (mol air)$^{-1}$ in that ~~each~~ curve. Only curves with mean incident PAR greater than 1200 μmol PAR m^{-2} s^{-1} have been used. Coloured points: normalised A_l calculated from observed c_i and incident PAR for each data point in the curve and the mean T_{leaf} observation for each curve, using the JULES relations. The JULES parameters are taken from the `repro-cox-1998` configuration (red triangles), the `global-C4-grass` configuration (blue circles) and fits to A. g. data (`tune-leaf` default configuration, cyan diamonds) and P. v. data (yellow diamonds). Model points have been calculated using the Leaf Simulator package.

3 Results and discussion

Figure 9, Figure 10 and Figure 11 show the model output for gross primary productivity (GPP), net canopy assimilation and latent heat flux for eight days during 1987. These dates sample a range of different vegetation states: 5th June is in the early growth stage, 2nd July and 11th July are in the peak growth stage, 23rd July, 30th July and 11th August are in the dry period and 17th August and 20th August are in the early senescence period (Verma et al., 1992). All of these dates comply with the

Figure 6. Ratio of ~~Leaf~~ internal to external CO_2 against specific humidity deficit dq~~chamber CO_2 for A~~. Crosses are derived from leaf measurements of *Andropogon gerardii* ~~g.~~ (cyan) and other C4 grasses (black), taken in the Konza prairie (Jesse Nippert and Troy Ocheltree, published in Lin et al. (2015))~~P~~. Straight lines show Jakobs model for C4 plants i~~v~~.e. $c_i/c_a = f_0\left(1 - \frac{dq}{dq_{crit}}\right)$. Red dotted line: `repro-cox-1998`, blue dot-dashed line: `global-C4-grass`, green solid line: `tune-leaf`. Green dashed lines: varying dq_{crit}, and setting f_0 to the best fit to the Lin et al. (2015) data for this dq_{crit}. Black dotted lines: Medlyn model using g_1^{fit}, $g_1^{fit}/2$, $g_1^{fit}/4$, where g_1^{fit} is the value of the Medlyn model parameter g_1 fitted in Lin et al. (2015)~~(yellow~~) to their Konza Prairie C4 grass measurements. The green solid ~~from FIFESUBSCRIPTNBPHOSUBSCRIPTNBLEAFSUBSCRIPTNB46. Each~~ line (the `tune-leaf` configuration) is a good approximation to ~~from~~ the Medlyn model with $g_1 = g_1^{fit}$ (because they have both been fit to the same dataset). The green dot-dashed ~~A_l-c_i curve,~~ and green dotted lines have been tuned to be close to the Medlyn model lines with $g_1 = g_1^{fit}/2$ ~~was taken an approximately constant humidity~~ and $g_1 = g_1^{fit}/4$ respectively~~temperature~~.

Figure 7. Comparison of leaf dark respiration against leaf temperature relations from Polley et al. (1992) (black solid line) Kim and Verma (1991a) (black dotted ~~dashed~~ line), `repro-cox-1998` (red dotted line), `global-C4-grass` (blue dot-dashed line), tuned to A.g. (cyan dashed line), tuned to P.v. (yellow dashed line) and tuned to both A.g. and P.v. (green solid line). All lines assume no light inhibition of respiration. All JULES lines are top of the canopy (TOC) values without water stress. The lines that reproduce JULES configurations have been calculated using the Leaf Simulator package.

selection criteria described in Cox et al. (1998) (following Stewart and Verma (1992)). Days with, or directly after, significant rainfall have been avoided, in order to reduce the effect of evaporation from the canopy surface and bare soil. The model latent heat flux is compared to latent heat flux measurements in the FIFE_SF30_ECV_33 dataset. GPP and net canopy assimilation are derived from CO_2 flux measurements in FIFE_SF30_ECV_33, using the method in Cox et al. (1998). Further net canopy assimilation estimates have also been read from Kim and Verma (1991a) (see Section 5.7 for more information).

3.1 `repro-cox-1998` and `global-C4-grass` simulations

GPP in the `repro-cox-1998` simulation after 10am local time compares very well to GPP derived from the flux tower data (Figure 9), for all growth stages. This is expected, given that this simulation is designed to reproduce the model from Cox et al. (1998), which was tuned to this flux dataset. The `global-C4-grass` simulation reproduces the carbon fluxes reasonably well outside the dry period, although GPP is underestimated during the growth stages. For example, GPP is underestimated by approximately 30% during the middle of the day on 5th June. During the dry period, however, the `global-C4-grass` simulation poorly captures the early morning peak and subsequent decline in GPP indicated by the carbon flux observations. The `repro-cox-1998` run captures this behaviour through its response to leaf temperature. The diurnal cycle of air temperature on these days in shown in Figure S5 and modelled leaf temperature in Figure S6~~temperature~~. Recall that V_{cmax} in the `repro-cox-1998` simulation declines at leaf temperatures above 32°C. This

Figure 8. Leaf water potential observations for four days taken at FIFE site 4439 in 1987, published in Kim and Verma (1991a).

causes a decline in modelled carbon assimilation during the hottest parts of the day (this is demonstrated explicitly in additional runs in the supplementary material). However, as discussed in Section 2, the temperature response in the `repro-cox-1998` configuration ~~this temperature response~~ is not supported by observations in Knapp (1985) or Polley et al. (1992). Therefore, it appears that, while the model is successfully capturing the shape of diurnal cycle during the dry period, it is not achieving this with the correct physical process.

Similarly, net canopy assimilation in the `repro-cox-1998` simulation compares well to the time series derived from the flux tower observations, although it has lower leaf respiration, particularly on 23rd July and 30th July Figure 10. As discussed in Section 5.7, the leaf respiration values assumed when processing the flux measurements were based on observations of leaf respiration in Polley et al. (1992). In Section 2.3, we showed that the `repro-cox-1998` simulation underestimates leaf respiration compared to the Polley et al. (1992) dataset, particularly at the higher temperatures experienced during middle of the day in the dry period. While the `global-C4-grass` configuration also simulates lower leaf respiration values than seen Polley et al. (1992), a combination of a low bias in the GPP and a peak in V_{cmax} at higher temperatures (compared to the `repro-cox-1998` simulation) reduces the impact on net canopy assimilation.

The latent heat flux is reasonably well modelled in general in both ~~latent heat flux is well modelled in general in both~~ the `repro-cox-1998` and `global-C4-grass` simulations outside the dry period (errors in the peak of the diurnal cycle of less than 20%). However both simulations overestimate the latent heat flux during the dry period (Figure 11). This is expected, given that we have already shown that the canopy carbon assimilation is overestimated, ~~the net assimilation is also overestimated~~and stomatal conductance is proportional to the net leaf assimilation in the model~~at this site (,)~~.

3.2 `tune-leaf` simulations

The `tune-leaf` configuration generally overestimates both GPP (Figure 9) and net canopy assimilation (Figure 10) compared to the observations and the `repro-cox-1998` and `global-C4-grass` simulations. On days during the dry period, the `tune-leaf` simulation behaves characteristically similarly to the `global-C4-grass` simulation in that it also does not capture the mid-morning peak and subsequent decline in GPP and assimilation. When fitting the `tune-leaf` configuration in Section 2, we highlighted uncertainties in some of the key parameters, and we will now look at the effect of these in turn~~here~~.

Firstly, the `tune-leaf` configuration is based on observations of the dominant grass species at this site, *A. gerardii*. In Section 2, we also fitted parameters to another grass species at this site: *P. virgatum*, and a ‘combined’ set fitted to both species. Since *A. gerardii* is almost twice as abundant at this site in 1987 as *P. virgatum*, and in the absence of parameter fits to the other grass species at this site, we would estimate that the most representative parameters lie somewhere between these two parameter sets. Using this combined *A.g./P.v.* parameter set increases GPP and net canopy assimilation on the order of roughly

10% compared to using the set fitted solely to *A.g.* (Figure 9, Figure 10), from which we conclude that the error introduced from using the dominant grass species is relatively minor.

A key difference between the `tune-leaf` configuration and the other configurations is the introduction of a non-zero p_0. Figure 12 ~~shows~~ illustrates that varying p_0 from 0 (as in the `repro-cox-1998` and `global-C4-grass` simulations) to 0.4 has a strong effect on GPP, as expected. It demonstrates the importance of ensuring that the threshold for water stress is consistent with the 'unstressed' leaf observations we calibrated against. Continuing to use ~~tuned against, since using~~ p_0=0 with the newly-tuned unstressed ~~these new~~ parameters would have resulted in ~~GPP that is~~ much too low GPP during the early growth period~~that we were using for tuning~~. Recall also that changing p_0 can be considered a proxy for changing the critical soil moisture. Therefore these runs also demonstrate ~~and therefore this sensitivity to p_0 also demonstrates~~ the sensitivity to uncertainty in the soil properties.

The effect of varying the canopy structure factor on GPP can be seen in Figure 13. This can also be seen as a proxy for examining the effect of reducing LAI as it changes the effective LAI seen by the model radiation scheme. Varying ~~Reducing~~ the canopy structure factor in the range 0.8-1.0 has a negligible effect on GPP on these days. However, reducing the canopy structure factor from 0.8 to 0.3 ~~,~~ has a large, negative impact on GPP. As discussed in Section 2, this range ~~, and a reduction of this size in LAI~~ is inside the error given in the LAI dataset documentation~~(as discussed in). Varying the canopy structure factor in the range 0.8-1.0 has a negligible effect on GPP on these days~~. The error in LAI for this site therefore has a large impact on the modelled canopy carbon fluxes.

Less straightforward to investigate is the effect of the uncertainty in the calibration of the JULES ~~the humidity response of~~ c_i humidity response~~in JULES , parameterised by dq_{crit}~~. Recall that the observational dataset used in Section 2 had a large spread in c_i compared to its range of specific humidity deficit values. This made it difficult to tune the parameter dq_{crit} separately to the overall scaling factor f_0. We therefore take the approach of systematically varying dq_{crit} (while setting ~~we were unable to constrain this parameter from the FIFE observations, so we kept the same value as . We then fitted the parameter~~ f_0 to keep the best fit to the observations in Figure 6), to show qualitatively that a different humidity calibration can not improve the agreement with the GPP observations ~~be consistent with the observations at this dq_{crit}. Here we examine whether it is possible to find a value of dq_{crit} that will model the drop in GPP from mid-morning~~ during the dry spell. Figure 14 compares modelled GPP for three different ~~period. Decreasing~~ dq_{crit}, f_0 combinations: dq_{crit} =0.048, f_0 =0.59 (upper green dashed line), dq_{crit} =0.040, f_0 =0.64 (central green dashed line) and dq_{crit} =0.035, f_0 =0.68 (lower green dashed line) for four days during the dry spell. Plots of ~~such that the~~ specific humidity deficit on these days are given Figure S7. None of these parameter combinations are able to fit the steady but low rate of GPP ~~dq approaches or exceeds it~~ during the middle period of the day: they transition between almost no humidity-induced effect on GPP, to a sudden decline. The timing of this decline varies across the four days shown. This demonstrates that, while lower ~~in the drought period would cause a drop in modelled~~ c_i values in these runs during the day in the dry period can reduce GPP, the magnitude of the slope of c_i/c_a against dq is too large. These two effects can not be reconciled while still maintaining consistency with the unstressed observations in Lin et al. (2015). This implies that the Jacobs parameterisation used in JULES, where the relationship between c_i/c_a and specific humidity deficit does not vary over the course of the run, does not have the flexibility needed to capture the behaviour of GPP at this site.

3.3 What potential model developments could improve the diurnal cycle of JULES GPP at this site?

As we have seen, the `global-C4-grass` configuration, which is typical of how this site would be modelled in a global JULES run, is unable to capture the diurnal cycle of GPP (and also net canopy assimilation and latent heat flux) at this site ~~(see). This could push the net leaf assimilation into the c_i limited region, especially as tuning to the normalised A_l-c_i curve in increased the threshold at which the plant can be considered to be not limited by CO$_2$. We can test this by using a more extreme value of dq_{crit} of 0.0475 (and a corresponding value of f_0 of 0.95, to stay consistent with the relation) . shows 4 days~~ during the dry period in 1987. Replacing the generic C4 grass tile parameters with parameters that are calibrated to observations taken of vegetation at this particular site (the ~~where the GPP observations show a mid-morning peak followed by a decline. Using this extreme value of dq_{crit} produces a sharp dip in the modelled GPP on the 30th July, which is markedly different to the flat nature of the GPP observations after the mid-morning peak. The model produces a similar localised mid-afternoon dip on the 11th August, with its minimum close to the observations. However, neither the 23rd July nor the 10th August shows any visible difference between this extreme dq_{crit} and the standard~~ `tune-leaf` configuration) does not improve ability of ~~value. This clearly shows that~~ the model to capture the diurnal cycle in these fluxes. We have demonstrated that this conclusion is robust to uncertainties in LAI, soil moisture, leaf parameters, canopy parameters and soil parameters.

We will now explore a number of possible options for improving the standard representation of the dry period diurnal GPP cycle at this site. Firstly, the model diurnal cycle can be greatly improved via the careful selection of parameters in the existing leaf temperature-dependent calculation of V_{cmax}. This was demonstrated in the model runs in Cox et al. (1998), which we have closely reproduced with the `repro-cox-1998` configuration. This method has the advantage that it provides a close fit to data and does not require any changes to the model code. A disadvantage of this method is that the V_{cmax} model parameterisation becomes an effective parameterisation which no longer has a clear biological interpretation. It therefore becomes more difficult to constrain from results in the literature. The numerical success of this method is due to high leaf temperatures acting as a proxy for high atmospheric demand during the middle of the day in the dry period (Figure S6 and Figure S7). While these temperature parameters provide a good approximation at this site in this particular year, it does not follow that these same temperature parameter values would be appropriate for other locations, or at this location under a changing climate.

Secondly, the model could be extended to include a soil moisture effect on the internal leaf CO$_2$ concentration c_i. As we demonstrated in Section 3, the current expression for c_i in JULES can not simultaneously fit the unstressed observations and be able to reduce c_i to the required levels to affect GPP during the dry season without also increasing the strength of the response to specific humidity deficit. This results in the humidity-induced stomatal closure occurring too suddenly on ~~model does not have the flexibility to reproduce the observed diurnal cycle in GPP on low humidity~~ days during the dry period. Introducing a soil moisture dependence in c_i would allow c_i to be lower on days where soil water was limiting for all humidity levels, while maintaining the higher values on unstressed days. Zhou et al. (2013) and De Kauwe et al. (2015) both achieve this by adding a soil moisture dependence to the VPD term in the Medlyn conductance model (Medlyn et al., 2011). The Medlyn model is based on the theoretical argument that stomata should act to minimise the amount of water used per unit carbon gained, leading to a stomatal conductance $g_0 + 1.6\left(1+\frac{g_1}{\sqrt{D}}\right)\frac{A}{c_a}$, where g_0 and g_1 are free parameters~~, even if it is pushed into the more extreme region of parameter space~~.

As demonstrated in De Kauwe et al. (2015), the parameters in the Jacobs model (f_0, dq_{crit}) can be chosen so that the resulting $c_i : c_a$ ratio approximates the Medlyn model, for mid-range VPD values. The unstressed Konza Prairie C4 grass measurements used in Section 2 to calibrate the $c_i : c_a$ ratio in the

3.4 ~~Limitations of the current water stress representation in JULES and possible extensions~~

~~As we have seen, both the and~~ `tune-leaf` configuration were actually provided in Lin et al. (2015) as part of a comprehensive study to tune the g_1 parameter in the Medlyn model for different vegetation types (with $g_0 = 0$). Using the Medlyn model with their calibrated g_1 value ($g_1^{fit} = 1.04$) does indeed give a similar c_i/c_a to our `tune-leaf` configuration (Figure 6, solid green line).

Therefore, to investigate the effect of a soil moisture-dependent g_1 on GPP, we can set the JULES c_i/c_a relation to mimic a lower g_1, and try this out on days with low soil moisture. For this test, we choose JULES parameter values that provide a rough approximation to the Medlyn model with $g_1 = g_1^{fit}/2$ and $g_1 = g_1^{fit}/4$ (Figure 6, dot-dashed and dotted green lines). These reductions in g_1 are well within the range observed in Zhou et al. (2013) for a range of different vegetation types under water-limited conditions. The resulting JULES parameter values are given in Table 4. Figure 15 demonstrates that lowering c_i/c_a in this way is able to qualitatively reproduce the shape of the ~~simulations are unable to capture the~~ diurnal cycle of GPP in ~~, net canopy assimilation and latent heat flux during~~ the dry period. The run mimicking $g_1 = g_1^{fit}/2$, ~~at FIFE site 4439~~ in particular, is a very good match to the observations. This shows the potential value of extending JULES to allow interaction between the plant response to soil moisture dependence and VPD. ~~1987. The simulation is more successful, but this response is mediated by a temperature dependence in leaf carbon assimilation which is not supported by observations.~~

Another way to implement this interaction in JULES would be to add a ~~Other studies have argued that the dry period diurnal cycle at this site can by captured via an explicit~~ dependence on leaf water potential, since leaf water potential is affected by both soil moisture (water supply) and VPD (atmospheric water demand). As discussed in Section 2.3, there is an observed relationship between leaf water potential and leaf assimilation in grass species at this site~~, and leaf potential is lowered not just by low values of soil moisture, but also by the high values of atmospheric VPD that occur during the middle of the day in the dry period~~.

Previous studies have demonstrated that models with an explicit dependence on leaf water potential can successfully capture the dry period diurnal cycle at this site. Kim and Verma (1991a) were able to qualitatively capture the mid-morning peak and subsequent decline in net canopy photosynthesis on 30th July at this site, using a model in which both V_{cmax} and J_{max} had a dependence on their leaf water potential measurements. Furthermore, Kim and Verma (1991b) were able to reproduce this ~~similar~~ behaviour in canopy conductance at this site on 30th July and 11th August 1987 using a model that included an explicit dependence on observed leaf water potential, in addition to ~~as well as~~ a direct dependence on VPD. ~~This implies that one possible way to improve the performance of C4 vegetation inJULES during dry periods would be to include a parameterisation of leaf water potential within the model , used as part of the calculation of carbon fluxes during water stress conditions.~~

Leaf water potential is not currently modelled explicitly within JULES. Typically, in plant hydraulic models, leaf water potential is calculated assuming a steady-state water balance, using the soil water potential, transpiration, and leaf-to-root and root-to-soil resistance terms (as in, e.g. Newman (1969)). Adding this to the JULES code is technically non-trivial as water stress is currently applied to leaf-level processes before transpiration is calculated. Also, modelling the plant resistances would require additional input parameters, which would need to be constrained from observations.

Stress parameterisations involving leaf water potential come in a range of complexities. The simplest involve inserting a leaf water potential-dependent stress factor into an existing part of the model e.g. the limiting photosynthesis rates as in Kim and Verma (1991a), or stomatal conductance, as in Kim and Verma (1991b) and Tuzet et al. (2003). More sophisticated models include the plant hydraulics as part of schemes incorporating risk-benefit analysis (e.g. Sperry et al. (2017); Eller et al. (2018)) and/or chemical signalling (e.g. Tardieu and Davies (1992); Dewar (2002); Huntingford et al. (2015)).

Finally, another way to improve the diurnal cycle of GPP in the dry period would be to incorporate a parameterisation of leaf rolling. For example, effective leaf area available to the radiation scheme could be decreased during hot, dry weather. ~~Although it improved the fit to observations, the leaf potential-based model in~~ Kim and Verma (1991a) attribute the residual overestimation of ~~still overestimated~~ net canopy carbon assimilation on days during the dry period of their leaf water potential-based model to this effect. It would therefore be interesting to investigate the contribution that leaf rolling makes to the overall plant water use strategy. However, while the occurrence of leaf rolling/folding at the FIFE site has been recorded, the effect has not been quantified. This would be a necessary first step for modelling this process at this site. ~~. They speculated that this could be due a decrease in apparent LAI caused by leaf rolling . As discussed in , leaf rolling is an observed strategy of A. gerardii, in response to drought conditions , which cannot be captured by the current version of the model. It would be useful to investigate whether a parameterisation of leaf rolling could be added in the future. It would also be valuable to include the decline in leaf nitrogen observed by .~~

3.4 Can the FIFE dataset make a useful contribution to current-day JULES evaluation and development work?

A global land-surface model such as JULES needs to perform well for a wide range of climate regimes, time scales, spatial scales and vegetation types. Model evaluation or development work needs to represent this variety. The availability of comprehensive databases, such as FLUXNET (Baldocchi et al., 2001) and TRY (Kattge et al., 2011), have revolutionised land-surface science by giving easy access to observations from a wide variety of sources, in a common format. Given this context, why would a modeller consider also using the FIFE dataset?

Firstly, FIFE provides an ideal case study for improving the model representation of water stress on carbon and water fluxes in JULES in tallgrass prairie. While, at one time, tallgrass prairie extended over 10% of the contiguous United States (Fierer et al., 2013), it has declined 82-99% since the 1830s due to agricultural use (Sampson and Knopf, 1994; Blair et al., 2014a). However, grasslands in general (including other grass- and graminoid-dominated habitats, such as savanna, open and closed shrubland, tundra) cover more terrestrial area than any other single biome type (up to 40 % of Earth's land surface (Blair et al., 2014a)). It is therefore important to include lots of examples of grasslands in any global analyses of vegetation responses to changing conditions. The Konza Prairie LTER site, where FIFE was based, has been used extensively to investigate the dynamics and trajectories of change in temperate grassland ecosystems, including drivers such as fire, grazing, climate, nutrient enrichment (see Blair et al. (2014b) for a review).

FIFE looked at the processes for representing water stress in detail, and intensively studied the relevant factors. This has led to a wide variety of complementary observations, and literature specifically focussing on how this data can be used to inform models. LAI is a good illustration of this advantage. As we have discussed, LAI is an important parameter for modelling canopy water and carbon fluxes. LAI was measured by multiple groups at FIFE, directly and indirectly, and the large differences found between the different attempts was fully explored at the time. We can use their results to inform our own use of these datasets.

When adding a new process to a global land-surface model, it is important to tune new parameters to a comprehesive range of datasets. For example, as mentioned in Section 3.3, Lin et al. (2015) use data for 314 species from 56 sites across the world to tune the new g_1 parameter introduced in the Medlyn model of stomatal conductance for key plant functional types. This breadth of sites and vegetation types is essential. Each site contributed leaf gas exchange observations taken under similar protocols to allow a carefully controlled common analysis.

Access to individual experiments, which have investigated the combined effect of a wide range of processes, such as FIFE, can play a complementary role in land-surface evaluation and development. For example, FIFE provides cases where improving an individual process in isolation degrades overall model performance. As we have shown, calibrating unstressed model V_{cmax}(T=25°C) from leaf observations without also calibrating when the model is considering the vegetation to be unstressed significantly underestimates early-season GPP. Similarly, tuning the model parameters to improve the fit to canopy GPP and evapotranspiration can result in an unrealistic temperature dependence of V_{cmax}. Looking at sites in a holistic way can also highlight complications or influences that might not *a priori* have been considered, such as leaf rolling in our case.

There are two main disadvantages to the use of FIFE in evaluation and model development studies. The first is the limited time period: observations are available for a period of up to three years, with some key measurements only undertaken during the intensive field campaigns. Where long term effects are being studied, alternative datasets would need to be used.

The second disadvantage is that it is relatively more time consuming to add FIFE to an evaluation study, compared to adding an extra site from one of the large, standardised databases such as FLUXNET. This is partly because FIFE provides a choice of different datasets to use for forcing, calibrating parameters and evaluation, which takes time to investigate. It is also partly because, although the data is easily downloadable, well documented and in common file formats, is still needs to be manipulated into a format that can be used in JULES runs. We aim to address this issue by providing a suite that can be used to pre-process the FIFE data and run JULES with the configurations described in this manuscript (see the ‘code and data availability’ section).

This aim is central to the provision of this manuscript. FIFE is the first ‘JULES golden site’, a concept was launched at the annual JULES meeting 2018. A JULES golden site is a site targeted by the JULES community because it can help address one of the key science questions facing JULES and has high-quality observational data that can be used to drive JULES and evaluate the output. It creates a network of researchers within the JULES community with experience of how this site can be exploited for JULES development, with input from site investigators. A key component is the provision of shared runs and evaluation datasets, which can be gradually expanded and improved.

In our study, we have focussed on the contribution that FIFE can make to the development of water stress in JULES. This has governed the choices we have made when setting up our configurations, e.g. choosing to prescribe LAI and soil moisture. However, we note here that FIFE could also be used to investigate other processes, such as ~~on a tallgrass prairiesite. The extensive range of observations available means that the FIFE dataset would also be very useful for looking at other processes. These include~~ plant and soil respiration (~~see the discussion in~~ Section 5.7), the seasonal decline in leaf nitrogen (Knapp, 1985) and the modelled energy balance (Kim and Verma, 1990a; Colello et al., 1998)~~(see, for example, and)~~.

	`repro-cox-1998`	`global-C4-grass`	`tune-leaf`
Radiation	Site averaged product Betts and Ball (1998). No diffuse radiation needed.	Site averaged product Betts and Ball (1998). Diffuse radiation from shortwave radiation using method in Weiss and Norman (1985).	Site averaged product Betts and Ball (1998). Diffuse radiation from shortwave radiation using method in Weiss and Norman (1985).
Other met. data	Site averaged product Betts and Ball (1998), apart from air pressure, which is set to a constant.	Site averaged product Betts and Ball (1998).	Site averaged product Betts and Ball (1998).
Leaf Area Index	Prescribed using obs. from Stewart and Verma (1992)	Prescribed using obs. from Stewart and Verma (1992)	Prescribed using obs. from Stewart and Verma (1992)
Canopy height	Prescribed using obs. from Verma et al. (1992)	Prescribed using obs. from Verma et al. (1992)	Prescribed using obs. from Verma et al. (1992)
Soil layers	0.1m, 0.25m, 0.75m and 2.0m	0.1m, 0.25m, 0.75m and 2.0m	0.1m, 0.25m, 0.75m and 2.0m
Soil moisture	Prescribed using obs. from Stewart and Verma (1992), no variation with depth.	Prescribed using obs. from Stewart and Verma (1992), variation with depth obtained from pre-processing with an offline version of the JULES hydrology code.	Prescribed using obs. from Stewart and Verma (1992), variation with depth obtained from pre-processing with an offline version of the JULES hydrology code.
Wilting and critical vol. soil moisture	Cox et al. (1998).	Cox et al. (1998).	Cox et al. (1998).
Soil moisture stress	One stress factor calculated ('bucket approach'). $p_0 = 0$.	Stress factor for each soil layer weighted by root distribution. $p_0 = 0$.	Stress factor for each soil layer weighted by root distribution. $p_0 = 0.3$.
Canopy scheme	'Big leaf' approximation.	Layered canopy, direct and diffuse beams, sunflecks.	Layered canopy, direct and diffuse beams, sunflecks.
PFT parameters (see Table 3)	Cox et al. (1998)	Harper et al. (2016)	Some tuning to site observations, as described in Section 2.

Table 1. Model settings for the runs at FIFE site 4439 for 1987. Further descriptions of the model setup can be found in Section 2 and the choice of FIFE observations in Section 5.

Figure 9. The diurnal cycle of GPP at site 4439 in the FIFE area for 8 days in 1987: 5th June (early growth), 2nd July and 11th July (peak growth), 23rd July, 30th July and 11th August (dry period) and 17th August and 20th August (early senescence). Green band show uncertainty from fitting plant parameters to *A. gerardii* compared to fitting to both *A. gerardii* and *P. virgatum*.

Figure 10. The diurnal cycle of net canopy assimilation A_c at site 4439 in the FIFE area for 8 days in 1987: 5th June (early growth), 2nd July and 11th July (peak growth), 23rd July, 30th July and 11th August (dry period) and 17th August and 20th August (early senescence). Green band show uncertainty from fitting plant parameters to *A. gerardii* compared to fitting to both *A. gerardii* and *P. virgatum*.

Figure 11. The diurnal cycle of latent heat flux at site 4439 in the FIFE area for 8 days in 1987: 5th June (early growth), 2nd July and 11th July (peak growth), 23rd July, 30th July and 11th August (dry period) and 17th August and 20th August (early senescence). Green band show uncertainty from fitting plant parameters to *A. gerardii* compared to fitting to both *A. gerardii* and *P. virgatum* (upper limit corresponds to the combined *A. g., P. v.* fit, lower limit to the *A.g.* fit (i.e. the default `tune-leaf` configuration).

Figure 12. The diurnal cycle of GPP at site 4439 in the FIFE area for 8 days in 1987: 5th June (early growth), 2nd July and 11th July (peak growth), 23rd July, 30th July and 11th August (dry period) and 17th August and 20th August (early senescence). Green band shows how `tune-leaf` simulation would vary for p_0 in the range 0 to 0.4 (lower limit corresponds to p_0=0, upper limit to p_0=0.4)~~0-0.4~~.

Figure 13. The diurnal cycle of GPP at site 4439 in the FIFE area for 8 days in 1987: 5th June (early growth), 2nd July and 11th July (peak growth), 23rd July, 30th July and 11th August (dry period) and 17th August and 20th August (early senescence). Green band shows how `tune-leaf` simulation would vary for a canopy structure factor a in the range 0.3 to 1 (upper limit corresponds to a=1, lower limit to a=0.3). ~~1.~~

Figure 14. The diurnal cycle of GPP at site 4439 in the FIFE area for 4 days in during the dry period of 1987. Solid green lines uses the ~~Green band shows how~~ `tune-leaf` configuration. Dashed dashed green lines show how GPP varies ~~simulation would vary~~ if ~~dq_{crit}, f_0 were changed from the default values of~~ dq_{crit} is increased~~=0.075~~, while f_0 is changed ~~=0.675~~ to maintain the best fit to the Konza prairie C4 grass observations in Lin et al. (2015) (Upper~~more extreme values dq_{crit}=0.0475~~, middle and lower dashed lines correspond to parameter combinations a, b, c respectively, as defined in Table 4)~~f_0=0.95~~.

4 Conclusions

In their closing remarks, Sellers and Hall (1992) state that "FIFE created an environment for the discussion of all aspects of the land surface component of Earth remote sensing and Earth system modeling and provided a data set which has been and continues to be used to test models and algorithms." Our study ~~This paper~~ demonstrates that this is still the case, twenty-five years after this remark, and ~~over~~ thirty years since the experiment itself. There is a ~~collection of its first year of data. FIFE continues to be a valuable resource for the land-surface modelling community, due to the~~ wealth of available data and ~~the~~ extensive analysis in the literature, particularly on ~~. Furthermore,~~ the response of vegetation carbon and water fluxes to periods of low water availability.

Historically, ~~dry spells was an area of research that was particularly prominent in the FIFE literature, and~~ FIFE observations were used to derive the original soil moisture stress parametrisation in ~~that was incorporated into~~ JULES. This early model was extremely successful in fitting the canopy net assimilation and water fluxes, during both dry and wet periods (Cox et al., 1998). However, a typical modern-day configuration of JULES, from Harper et al. (2016), which models the FIFE vegetation with generic C4 grass parameters, could not reproduce the observed diurnal cycle of carbon and water fluxes during the period of low water availability. Calibrating the plant parameters to site observations did not solve this problem, nor could it be explained by the large observational uncertainties in leaf area index, soil moisture, and soil properties. Reproducing the original configuration in Cox et al. (1998) illustrated that the temperature dependence of the maximum rate of carboxylation of Rubisco V_{cmax} in the model was key for reducing modelled photosynthesis rates during the hottest parts of the day in the dry period, since model V_{cmax} declined steeply at the leaf temperatures experienced on these days~~therefore makes FIFE an ideal test case for evaluating and improving this process.~~

~~JULEScan closely reproduce the original runs in . Extending this setup to make use of all the subsequent developments that have been incorporated into JULES demonstrates that the current version of the model is still able to successfully reproduce the net canopy assimilation and latent heat energy flux reasonably well through the season~~. However, this temperature response was not supported by the available leaf-level gas exchange observations. With a more realistic temperature response, this configuration was no longer ~~it highlights some important issues. JULES is not currently~~ able to capture the reduction of photosynthesis during the middle of the day in the dry period either.

FIFE therefore provides a robust example of how the current processes that govern the way that vegetation in JULES responds to water availability do not behave realistically during dry spells for this type of grassland. This deficiency could be addressed by allowing the effect of soil moisture availability and vapour pressure deficit on stomatal conductance to interact, for example, via leaf water potential. FIFE is thus a useful site to consider when evaluating the benefits of new water stress parameterisations to JULES, particularly those with an explicit representation of plant hydraulics~~diurnal cycle of net canopy photosynthesis at this C4 grass site, due to the lack of a strong dependence on the canopy vapour pressure deficit (indirectly or directly). The temperature response of V_{cmax} can be tuned to compensate for this , but it is more desirable for the model to respond to high temperature stress and high water stress individually. These runs also showed how the default water stress parameterisation can result in large reductions in photosynthesis during periods that are not considered water-limiting at the site~~ . ~~Re-tuning the water stress parameterisation to address this issue must be done in conjunction with a re-tuning of the unstressed photosynthesis parameters.~~

FIFE can play a role in JULES evaluation and development only as one small component of a comprehensive range of datasets, covering different climate regimes, time scales, spatial scales and vegetation types. FIFE is valuable partly due to the concentration of overlapping datasets. Key observables such as ~~The water stress parametrisation, and therefore photosynthesis and transpiration in JULES , are also sensitive to the observational uncertainty in~~ leaf area index, soil moisture, and soil properties, from independent investigations during FIFE, have been intensively analysed ~~. These have been extensively studied at FIFE in independent investigations~~ and yet still show a wide spread. This illustrates the intrinsic variability of these parameters, which ~~, leading to large modelling uncertainties. This is an important issue when tuning JULES based on site data and~~ must be carefully considered when scaling up to gridded, global runs. FIFE also provides clear examples of how calibrating one process to observations can reduce the overall model performance, due to compensating biases (such as calibrating the unstressed parameters without also checking the time period during which the model considers the vegetation to be unstressed). ~~larger scale runs. The FIFE data also indicates that it could be beneficial to extend JULES to include other drought strategies observed at the site, such as leaf rolling and senescence.~~

Confidence that the model is capturing key processes is necessary if the model is being run into new regimes, such as when forced with climate projections. This ability to disentangle and evaluate individual processes emphasises the value that intensive experiments such as FIFE have towards the larger modelling community evaluation efforts. In order to facilitate the inclusion of FIFE data in comprehensive model evaluations, this manuscript is accompanied by a release of the ~~study provides clear examples of how improving one part of the model may initially appear to worsen the fit to observations, if there were compensating biases. It requires detailed site data to disentangle these effects. This detailed data needs to be available for a wide variety of sites, with different climates and vegetation, to avoid the risk of over-tuning to one site. It is hoped that this study can be part of the larger effort of developing and evaluating JULES. With this aim, the publication of this manuscript will be accompanied by the release of~~ full set of data processing and configuration files needed to reproduce these model simulations~~process the data downloaded from ORNL-DAAC and reproduce these JULES runs (see the ‘code and data availability’ section for more information)~~. It is intended that this suite of files ~~form a living set of configurations, which~~ will continue to develop in the future as additional parts of the model are evaluated against the FIFE dataset, so that ~~and~~ the JULES community can build ~~builds~~ up a comprehensive body of knowledge of data and model runs at this site.

Figure 15. The diurnal cycle of GPP at site 4439 in the FIFE area for 4 days in during the dry period of 1987. Solid green lines uses the `tune-leaf` configuration. The c_i to c_a ratio in this configuration closely corresponds to the c_i to c_a ratio for C4 grasses in the Konza prairie in Lin et al. (2015), using the Medlyn model and fitting the Medlyn model parameter g_1 to measurements taken in 2008 ($g_1 = g_1^{fit}$=1.04 kPa$^{-0.5}$). The dot-dashed lines and dotted lines show the results from fitting the JULES parameters dq_{crit} and f_0 to approximate the Medlyn model when $g_1 = g_1^{fit}/2$ and $g_1 = g_1^{fit}/4$ (the parameter values are given in Table 4).

Code and data availability. JULES can be downloaded from the JULES FCM repository on the Met Office Science Repository Service at https://code.metoffice.gov.uk/trac/jules (registration required). We use JULES version 5.0 (tag 'vn5.0'), which corresponds to revision 9522. The Leaf Simulator can be downloaded from https://code.metoffice.gov.uk/trac/utils. Where data points have been read directly from published plots, this was done with the EasyNData tool (Uwer, 2007). The three JULES simulations described in this study can be reproduced using the rose suite u-bb181, available at https://code.metoffice.gov.uk/trac/roses-u/browser/b/b/1/8/1/trunk. This suite also contains instructions for downloading the driving data from ORNL-DAAC and a script to pre-process the driving data, including calculating the diffuse radiation fraction.

5 FIFE observations

This section discusses the use of the observations and the alternative datasets considered. All of these datasets are available either in the published literature or available for download from the Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC). A list of all the ORNL-DAAC datasets referred to in this manuscript is given in Table 2.

5.1 Driving data

This study used a 30 minute resolution combined data product (FIFE_FFOAMS87_88) from observations from Portable Automatic Meteorological Stations (AMS) across the FIFE area, described in Betts and Ball (1998). Descriptions and references to all the FIFE datasets available from Oak Ridge National Laboratory Distributed Active Archive Center, are given in Table 2. Extensive manual processing was undertaken to clean the station data before it was combined into the site-averaged data product (Betts and Ball, 1998).

The fraction of diffuse radiation is an important driving variable when the full layered canopy scheme is used in JULES Mercado et al. (2007), although it is frequently not available and so set to a constant. For our study, we calculate diffuse radiation from shortwave radiation using the method in Weiss and Norman (1985). This method was used successfully at the FIFE site by Kim and Verma (1991a) and Kim and Verma (1991b). We also investigated using the hourly cloud observations of Marshall AAF, KS, approximately 12 km west of the FIFE site, which were included as part of the FIFE_FFOAMS87_88 dataset, which we converted to diffuse radiation fraction using the linear relationship given in Butt et al. (2010). This relationship was derived for two sites in the Amazon, but we confirmed that this was approximately consistent with observations of sites in the Southern Great Plains region of Oklahoma and Kansas in Still et al. (2009). However, we found that the cloud cover observations were not sufficiently consistent with the shortwave radiation used to drive the model runs. There are also total cloud cover observations from the FIFE area available in FIFE_FFOAMS87_88, but this had a period of missing data between the end of August and the middle of September. It would be interesting to compare these results to the approximation for diffuse radiation used by Gu et al. (2002) for a tallgrass prairie site in Oklahoma.

Colello et al. (1998) also carried out model runs driven by the site-averaged product FIFE_FFOAMS87_88, and applied corrections to shortwave downward radiation, longwave downward radiation and wind speed using observations from site 4439. In our study, we do not apply local corrections to the site-averaged meteorological data. However, this may be useful to consider in the future.

5.2 Leaf area index

The green Leaf Area Index values used in this paper are destructive measurements for FIFE site 4439, read from Figure 1 of Stewart and Verma (1992), which were taken roughly once a fortnight between 26th May and 11th October 1987. These observations are plotted in Figure 16. They correspond closely to the green LAI observations from Verma et al. (1992) and are similar to the green LAI observations for this site given in Sellers et al. (1992) for the intensive field campaigns. The LAI values used in the Cox et al. (1998) modelling study are very similar to these datasets. Destructive LAI measurements for grass LAI, non-grass LAI and total LAI are available as part of the FIFE_VEG_BIOP_135 dataset. However, the total LAI in FIFE_VEG_BIOP_135 is substantially different from the measurements in Stewart and Verma (1992), Verma et al. (1992) and Sellers et al. (1992). This was investigated in detail at the time (Kim et al., 1989). The FIFE_VEG_BIOP_135 dataset documentation estimates that there is standard error of the mean LAI in their data of around 75% due to the inherent variability of prairie vegetation and a variation of about 25% can be attributed to leaf curling or folding as the leaves passed over the detector, particularly an issue for drought-stressed leaves. Foliage Area Index measurements (i.e. includes green leaves, dead leaves, stems) are available in FIFE_LB_UNL_42 for site 4439 in 1987, and plotted in Figure 17. FIFE_LIGHTWND_43 and FIFE_LB_KSU_41 also have Foliage Area Index measurements for site 4439, but these were taken in 1988-9, not 1987.

We also experimented with the internal phenology scheme in JULES. Calculating LAI dynamically with the phenology scheme would remove the need to prescribe LAI. However, we found that this scheme did not have the flexibility to reproduce the observed seasonal cycle of LAI.

Figure 16. Leaf area index observations for site 4439 for 1987. Left: data from FIFE_VEG_BIOP_135. Right: literature values. Plot includes data extracted from Stewart and Verma (1992) Figure 1 and Cox et al. (1998) Figure 1, total LAI and green LAI from Sellers et al. (1992) for the intensive field campaigns and green LAI data from Table 4 in Verma et al. (1992).

Figure 17. Foliage Area Index observations from FIFE_LB_UNL_42 for site 4439 in 1987.

5.3 Soil moisture

The soil moisture data for site 4439 presented in Figure 1 of Stewart and Verma (1992) were created from a combination gravimetric measurements and neutron probe measurements. The gravimetric measurements were taken in the top 0.1m soil daily during the FIFE intensive field campaigns and weekly between campaigns. The neutron probe measurements were taken at different depths on 15 dates, at approximately weekly intervals between the end of May and the beginning of September 2017. These measurements were interpolated in Stewart and Verma (1992) using daily precipitation and evaporation measurements to get a daily soil moisture values for the 0-1.1m soil layer. Stewart and Verma (1992) also observed ‘virtually no seasonal variation’ in soil moisture below 1.1m. The data from Stewart and Verma (1992) for the top 1.1m of soil corresponds very closely to the 0-1.6m soil moisture values used in Cox et al. (1998) on their selected days, as illustrated in Figure 18. Stewart and Verma (1992) also presents data for an ungrazed site in the FIFE area, and state that, while the ungrazed and grazed sites received very similar season totals of precipitation, individual storms resulted in differences in soil moisture (which gives a possible motivation for using site 4439 precipitation measurements over the site-averaged data product we use here).

Figure 18. Soil moisture data from Cox et al. (1998), compared to the derived time series of top 1.1m soil moisture in Figure 1 of Stewart and Verma (1992). Both datasets are for FIFE site 4439 in 1987.

ORNL-DAAC contains two main datasets of soil moisture observations on levels that can be considered for site 4439 for 1987: FIFE_SM_NEUT_111, which contains measurements carried out at site 4439 and FIFE_FFONEU87_100, which is a site-averaged product for the FIFE area (Betts and Ball, 1998). These are plotted in Figure 19 for 1987. It can be seen that, at lower depths, the site 4439 measurements are considerably lower than the site-averaged product. For 1988, however, the site-averaged product is mostly within or near the edge of the spread of observations at site 4439, up to approximately 120cm. Neither of these datasets are consistent with the Stewart and Verma (1992) site 4439 dataset when summed over the top 1.1m. The FIFE_SM_NEUT_111 for site 8639, on the other hand, is consistent with the Stewart and Verma (1992) site 8739 dataset. The documentation for FIFE_FFONEU87_100 also cautions that the 20cm neutron probe data is ‘suspect’ as the range of the probe exceeds 20cm in dry soil and says that it is ‘inconsistent’ with the rest of the profile in 1987. It has been linearly interpolated between observation dates. Plots of observed soil profiles for 9th July and 31st July 1987 are presented in Kim and Verma (1990a). Soil profiles for individual days are also presented in Colello et al. (1998), which are consistent with the neutron probe measurements in FIFE_SM_NEUT_111, but not the gravimetric measurements. Given these inconsistencies, we chose not to use the soil moisture observations for individual levels to directly drive our simulations.

Folder name	Dataset Reference	Description
FIFE_FFOAMS87_88	Betts (1994a)	Site Averaged AMS Data, published in Betts and Ball (1998)
FIFE_PHO_LEAF_46	Norman (1994a)	Leaf Photosynthesis Rates, published in Polley et al. (1992)
FIFE_VEG_BIOP_135	Nelson et al. (1994)	Biophysical properties of the vegetation at the FIFE study area collected for FIFE by the staff of the Evapotranspiration Laboratory at Kansas State University under the direction of E.T. Kanemasu, and by the staff of the University of Nebraska, Lincoln under the direction of B. Blad. The dedicated efforts of A. Nelson, J. Killeen, L. Ballou, T. Shah, and C. Hays in collecting and preparing these data is particularly appreciated.
FIFE_LEAF_H2O_126	Blad and Walter-Shea (1994b)	Total Leaf Tissue Water Potential data collected by B.L. Blad, E.A. Walter-Shea, C.J. Hays, and M.A. Mesarch of the University of Nebraska.
FIFE_LB_UNL_42	Blad and Walter-Shea (1994a)	Leaf Area Index and PAR Determined from the UNL Light Bar Data collected under the direction of B.L. Blad and E.A. Walter-Shea at the University of Nebraska. The dedicated efforts of C.J. Hays and M.A. Mesarch in the collection and preparation of these data is particularly appreciated.
FIFE_LIGHTWND_43	Shah and Kanemasu (1994b)	Indirect Leaf Area Index Obtained from the KSU Light Wand data collected by staff of Kansas State University under the direction of T. Shaw and E.T. Kanemasu. The contribution of these data is appreciated.
FIFE_LB_KSU_41	Shah and Kanemasu (1994a)	Leaf Area Index and PAR Determined from KSU Light Bar Measurements collected as part of the KSU staff science effort directed by Dr. E.T. Kanemasu.
FIFE_SM_NEUT_111	Kanemasu (1994a)	Neutron Probe Soil Moisture data collected for FIFE by the staff and students of the Evapotranspiration Laboratory at Kansas State University under the direction of Dr. Edward Kanemasu. The dedicated effort of A. Nelson, T. Shah and G. Harbers in the collection and preparation of these data is particularly appreciated.
FIFE_FFONEU87_100	Betts (1994b)	Site Averaged Neutron Soil Moisture (Betts and Ball, 1998)
FIFE_SF30_ECV_33	Verma (1994)	Eddy Correlation Surface Flux Observations (UNL) collected by Dr. Shashi B. Verma.
FIFE_SOIL_CO2_105	Norman (1994b)	Soil CO_2 flux data, published in Norman et al. (1992).
FIFE_PHO_BOX_27	Asrar and Sellers (1994)	Canopy Photosynthesis data collected by G. Asrar of NASA HQ and P.J. Sellers of NASA Goddard Space Flight Center.
FIFE_SOILSURV_115	Huemmrich and Levine (1994)	Soil survey data obtained by the FIFE Information System staff from the US Dept. of Agriculture, Soil Conservation Service (USDA-SCS). Thanks are due to Dr. Elissa Levine who was instrumental in acquiring, interpreting, and preparing these data.
FIFE_SOILDERV_117	Sellers and Huemmrich (1994)	Soil Water Properties data set produced by the FIFE Information System staff using data collected by the FIFE staff science team.
FIFE_SOIL_REL_112	Hope and Peck (1994)	FIFE Level-3 Example Gridded Soil Moisture data provided by Drs. A. Hope and E. Peck. The assistance of Dr. James Wang, NASA, in furnishing PBMR soil moisture data was sincerely appreciated. Thanks to the FIS staff, especially Fred Huemmrich, Diana van Elburg-Obler and Jeff Newcomer, for providing information in such usable form. Thanks also to Eric Wood, Princeton University, for providing soil moisture data in digital form for the Kings Creek Basin.
FIFE_SOILHYDC_107	Kanemasu (1994b)	Soil Hydraulic Conductivity data collected for FIFE by the staff of the Evapotranspiration Lab at Kansas State University.
FIFE_SOILREFL_114	Huemmrich (1994)	Soil Reflectance Reference data obtained by the FIFE Information System staff from Stoner et al., 1980. The permission of Stoner et. al. to use these data is greatly appreciated.

Table 2. List of FIFE datasets from ORNL-DAAC referenced in this document. Each dataset is referred to by its folder name.

5.3.1 Derived soil moisture

In order to create a daily soil moisture time series on levels, which could be used to drive the `global-C4-grass` and `tune-leaf` runs, we used a python implementation of the JULES hydrology scheme. The soil layer thicknesses used were the same as in Harper et al. (2016), apart from the third soil layer, which was extended by 10cm. This meant that the total depth of the top three layers was 1.1m, which meant that we could constrain the sum of the soil moisture in the top three levels in our runs to be equal to the daily 0-1.1m soil moisture values from Stewart and Verma (1992). We assumed that positive changes in the 0-1.1m soil moisture were due to rainfall (with runoff, canopy evaporation and soil evaporation from that day already subtracted) and therefore added it to the top layer, while negative changes in the 0-1.1 m soil moisture were assumed to be due to transpiration (corrected for the transpiration flux from the lowest level and the flux between the lowest and second-to lowest layer), which was taken from the soil layers according to an exponential root distribution with efold depth d_r =0.5m. This d_r depth is the same as natural C4 grass in Harper et al. (2016). We used the same soil hydrological parameters as in our JULES simulations (described in Section 5.4).

The resulting derived soil moisture timeseries are shown in Figure 20 (left). As expected, the upper levels show more variability than the lower levels, which is consistent with the sitegrid 4439 and site-averaged soil moisture time series on levels (see Section 5.3) and approximately with the statement in Stewart and Verma (1992) that there was ‘virtually no seasonal variation’ below 1.1m. Figure 20 (right) compares the derived time series for soil moisture in the top soil level (10cm thickness) to the gravimetric soil moisture data for 2.5cm and 7.5cm from FIFE_SM_NEUT_111. While the fit is reasonable, given the spread in observations, it appears to indicate that the variability in the top level soil moisture is still underestimated. This could be due to the assumed root distribution (a lower d_r would lead to more water extracted from the upper layer), or the approximation that soil evaporation can be neglected on days without rainfall, or approximations made by Stewart and Verma (1992) when deriving the 1.1m soil moisture timeseries.

We also attempted two other methods for deriving a soil moisture time series on levels from Stewart and Verma (1992): using the transpiration from the `repro-cox-1998` run and editing the `repro-cox-1998` run so that soil moisture was no longer prescribed. The first method did not perform well, possibly due to the transpiration and soil moisture time series not quite being in step with each other. The second method worked well if the canopy capacity at zero LAI was reduced (in JULES, the canopy capacity is a linear function of LAI) and the PFT infiltration enhancement factor increased. Interestingly, Colello et al. (1998) concluded that they needed to change the infiltration and canopy interception capacity for this site. There was an issue capturing one of the peaks in the surface soil moisture in the spring, which was probably due to missing data in the rainfall dataset: the local day maximum in `FIFE_FFOAMS87_88` from day 130 to day 150 was 42.71mm, which occurred on day 147, which had 9 missing timesteps. In contrast, the local day maximum from for this interval in Stewart and Verma (1992) was much higher, at around 70mm.

5.4 Soil properties

This section discusses and compares the available measurements of the hydraulic, thermal and optical soil properties, which can be used as ancillary data for runs at FIFE site 4439. Soil in the FIFE area was extensively studied. At site 4439, the soil was classified as predominantly Dwight silty clay loam (Typic Natrustolls) (Verma et al., 1992). Colello et al. (1998) describes the soil column as being “about 140cm in depth, changing from silty-clay-loam to clay to gravel to impermeable bedrock".

In our simulations, each soil ancillary variable was set to be constant throughout the soil column. The two most important soil parameters are the ‘wilting’ soil moisture θ_{wilt} and ‘critical’ soil moisture θ_{crit}, which we define as the volumetric soil moisture at -0.033MPa and -1.5MPa respectively (following Cox et al. (1998) and Best et al. (2011)). These soil parameters enter directly in to the soil moisture stress calculation. In all of our simulations, θ_{wilt} was set to 0.205 and θ_{crit} was set to 0.387, taken from Cox et al. (1998) (which quotes Stewart and Verma (1992), although these values do not appear in this paper explicitly). In contrast, Verma et al. (1989) states that the surface (0 to 0.05m) wilting and critical soil moistures were approximately 15.0% and 39.4% respectively. It is also possible to obtain the wilting and critical soil moistures used in Verma et al. (1992), from comparing their extractable water values to volumetric soil moisture measurements from individual days in Cox et al. (1998). This leads to wilting and critical soil moistures of 20.1% and 34.8% respectively.

We used the Brooks and Corey (1964) relation between soil water content θ and absolute matric potential Ψ

$$\frac{\theta}{\theta_S} = \left(\frac{\Psi}{\Psi_S}\right)^{-1/b}, \tag{2}$$

where S denotes values at saturation, to obtain the Brooks-Corey parameter b and the soil water suction at saturation Ψ_S from the Cox et al. (1998) values of θ_{wilt} and θ_{crit}. The other hydraulic and thermal soil ancillary variables were calculated from the fraction of sand, silt and clay given for Dwight soil in FIFE_SOILSURV_115, averaged over 0-122cm, using the relations from Cosby et al. (1984). The soil albedo (0.162) was calculated from the Munsell color value for dry Dwight soil given in FIFE_SOILSURV_115, averaged over 0-122cm, using the relation in Post et al. (2000). This was consistent with the reflectance data for Dwight soil in FIFE_SOILREFL_114 (which had mean 0.153, standard deviation 0.055 and was taken at a range of wavelengths).

There are also measurements available at specified depths. FIFE_SOILSURV_115 contains observations for clay, silt, sand and organic carbon content, bulk density, wilting and critical soil moistures for Dwight soil at different depths (this data is from site 2731, but it states that this data can also be used for site 4439, because the two sites have similar soil series). The relations in Cosby et al. (1984) can be used to convert the clay, sand, silt fractions to the soil hydraulic and thermal parameters needed by JULES. These can be corrected for organic content using Dankers et al. (2011) and Chadburn et al. (2015). The FIFE_SOIL_REL_112 dataset contains site 4439 bulk density and soil water potentials at different volumetric soil contents (including the wilting and critical soil moistures). FIFE_SOILDERV_117 has soil porosity, saturated water potential and the b parameter from Eq. 2 for site 4439. Water retention curves plotted using this data are consistent with the data in FIFE_SOIL_REL_112 (not shown). Hydraulic conductivity for site 4439 is provided in FIFE_SOILHYDC_107. Bulk density can be converted to saturation volumetric soil moisture using the relation given in the FIFE_SOILDERV_117 documentation.

The resulting soil hydraulic and thermal parameters from these different methods are plotted in Figure 21, and shows that there are considerable differences between the different datasets. The large spread in the wilting and critical soil moistures is particularly important to note, since, as we have discussed, they both enter the soil moisture stress factor β explicitly, and therefore plant GPP and transpiration are very sensitive to variations in these parameters. The thermal and optical soil properties and the remaining hydraulic properties have a comparatively minor effect on GPP and evapotranspiration.

5.5 Canopy height

In this study, we used the canopy height observations presented in Table 2 of Verma et al. (1992): 0.4-0.6m, 0.6-0.75m, 0.75-0.9m for days 120-179, 180-239, 240-300 respectively for site 16 in 1987. Another available dataset for canopy height at this site is FIFE_VEG_BIOP_135, which is plotted in Figure 22, and shows considerable differences with the Verma et al. (1992) data, particularly in the 240-300 day period. As discussed in Section 5.2, the non-uniformity of the vegetation at this site is a significant source of error in these measurements.

5.6 Canopy dark respiration

Polley et al. (1992) shows leaf dark respiration as a function of leaf temperature for observations of *A. gerardii*, *S. nutans* and *P. virgatum* taken in the FIFE area in 1987 and fits the following relationship:

$$R_{dl} = \frac{0.0496T_l - 0.0157}{1 - 0.01158T_l}. \qquad (3)$$

When this relation was used in Cox et al. (1998), it was scaled up to the canopy level by multiplying by LAI, i.e. dark respiration was assumed to be constant on leaves through the canopy. In contrast, in the model presented in Kim and Verma (1991a), leaf respiration was calculated from

$$R_d = R_{d,25} \exp\left[45000(T_l - 25)/(298R(T_l + 273))\right], \qquad (4)$$

where $R_{d,25}$=1.55 μmol m^{-2} s^{-1}, R=8.314 J K^{-1} mol $^{-1}$ is the gas constant and T_l is the leaf temperature in °C and leaf dark respiration was suppressed by 50% when the absorbed PAR was greater than 20 μmol quanta m^{-2} s^{-1}, to account for the light dependency of mitochondrial respiration. Air temperature near the top of the canopy was used to approximate leaf temperature. Kim and Verma (1991a) scaled this leaf respiration up to the canopy level by considering the sunlit and shaded portions of the leaf separately.

In JULES, dark respiration decreases through the canopy in the same way as V_{cmax} and it is multiplied by the soil moisture stress parameter β. In the 'big leaf' approximation used in the `repro-cox-1998` run, V_{cmax} decreases through the canopy with light. In the layered canopy model with sunflecks used in the `global-C4-grass` and `tune-leaf` runs, the decrease of V_{cmax} through the canopy is set by an input parameter k_{nl}, and the leaf dark respiration is reduced by a factor of 30% above a light threshold.

5.7 Net canopy assimilation

In this study, we compared the net canopy carbon assimilation from the model (for Gross Primary Productivity (GPP) minus respiration from leaves) to two different datasets. The first dataset was read from Figures 1-4 in Kim and Verma (1991a), for 5th June, 2nd July, 30th July and 20th August 1987, which was obtained from eddy correlations of atmospheric CO_2, measured above the canopy. Leaf respiration was calculated from Eq. 4, as described in Section 5.6. The leaf respiration over the entire canopy was subtracted from the night-time CO_2 flux from the night following or proceeding the day under consideration, to calculate the other sources of respiration (soil, root), which were adjusted to daytime soil temperatures using a Q_{10} factor of 2.

The second net canopy carbon assimilation dataset was created from FIFE_SF30_ECV_33 observations of CO_2 flux from eddy correlation techniques using the procedure in Cox et al. (1998). The total respiration F_s in Cox et al. (1998) was fitted to the functional form proposed by Norman et al. (1992) for use when LAI measurements were not available, evaluated with FIFE data:

$$F_s = s_1 \left(\frac{\theta - s_2}{0.4 - s_2} \right) e^{s_3 (T_{s,10} - 25)}, \tag{5}$$

where $T_{s,10}$ is the 10cm soil temperature in °C and s_1, s_2 and s_3 are fitted parameters. Using air temperature in the place of the soil temperature, Cox et al. (1998) found that using this expression with the parameter values s_1=17.8μ mol CO_2 m^{-2} s^{-1}, s_2=0.2, s_3=0.062 °C^{-1} explained 50.7% of the variance in night-time CO^2 flux measurements at FIFE. Leaf-level dark respiration was calculated using Eq. 3, scaling from leaf-level to canopy level by multiplying by LAI, as described in Section 5.6, assuming that the leaf temperature and the air temperature were the same (we used the air temperatures in FIFE_SF30_ECV_33).

Canopy measurements taken in a Plexiglas chamber (FIFE_PHO_BOX_27) at 4 sites, including 4439, could possibly be used as an additional source of net canopy assimilation for comparison with the model. It would also be interesting to extend the analysis to include an evaluation of the modelled soil respiration. The model could be compared directly to the fitted expressions for soil respiration (with and without a LAI dependence) from Norman et al. (1992) or, alternatively, to the soil CO_2 flux measurements available in FIFE_SOIL_CO2_105.

Competing interests. The authors declare that they have no conflict of interest.

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Figure 19. Site-averaged soil moisture on levels from FIFE_FFONEU87_100 for 1987 (line) and individual observations of site 4439 in 1987 from FIFE_SM_NEUT_111 (points).

Figure 20. Left: Derived soil moisture dataset, on model soil levels. Right: Derived soil moisture in the top layer, compared to the gravimetric soil moisture measurements for 2.5cm and 7.5cm from FIFE_SM_NEUT_111.

Figure 21. Soil ancillary variables needed by JULES, using the notation from the JULES namelists. When JULES is set to use soil hydraulic characteristics from Brooks and Corey (1964), these are `b` (exponent in soil hydraulic characteristics i.e. b in Eq. 2), `hcap` (dry heat capacity in J m^{-3} K^{-1}), `sm_wilt` (volumetric soil moisture content at -1.5MPa, θ_{wilt}), `hcon` (dry thermal conductivity in W m^{-1} K^{-1}), `sm_crit` (volumetric soil moisture content at -1/30MPa, θ_{crit}), `satcon` (hydraulic conductivity at saturation in kg m^{-2} s^{-1}), `sathh` (absolute value of the soil matric suction at saturation Ψ_S in m) and `sm_sat` (volumetric soil moisture content at saturation θ_S).

Figure 22. Canopy height in cm for site 4439 for 1987 from FIFE_VEG_BIOP_135.

JULES notation	`repro-cox-1998`	`global-C4-grass`	`tune-leaf` A.g. (default)	`tune-leaf` A.g./P.v.	Description
`can_rad_mod`	1	6	6	6	Flag to select canopy radiation scheme (-).
`fd_io`	0.025	0.019	0.054	0.054	Scale factor for dark respiration (-).
`nmass_io`	0.015326	0.0113	0.025	0.02455	Top leaf nitrogen content per unit mass (kg N (kg leaf)$^{-1}$).
`vsl_io`	20.48	20.48	30.0	37.5	Slope in the linear regression between V_{cmax} and nitrogen per leaf area (μmol CO$_2$ g N^{-1} s^{-1}).
`lma_io`	0.137	0.137	0.0609	0.0574	Leaf mass per unit area (kg leaf m^{-2})
`tlow_io`	13.0	13.0	23.0	25.5	Lower temperature parameter in the V_{cmax} calculation (°C).
`tupp_io`	36.0	45.0	49.0	47.5	Upper temperature parameter in the V_{cmax} calculation (°C).
`q10_leaf_io`	2.0	2.0	1.0	1.0	Q_{10} factor in V_{cmax} calculation (-).
`dq_crit_io`	0.078	0.075	0.070	0.070	Critical humidity deficit dq_{crit} (kg H$_2$O per kg air)
`f0_io`	0.82	0.8	0.53	0.53	Ratio of internal to external CO$_2$ pressure when canopy level specific humidity deficit is zero f_0 (-).
`fwe_c4`	2.0E4	2.0E4	1.0E4	1.25E4	
`fsmc_mod_io`	1	0	0	0	Integer indicating weighting of soil layers in water stress factor.
`fsmc_p0_io`	0.0		0.3	0.3	Scaling factor p_0 in water stress factor calculation .
`can_struct_a_io`	1.0	1.0	0.8	0.8	Canopy clumping factor a.
`rootd_ft_io`	1.4	0.5	0.5	0.5	Parameter determining the root depth (m).
`alpha_io`	0.034	0.04	0.048	0.053	Quantum efficiency (mol CO$_2$ (mol PAR photons)$^{-1}$).
`omega_io`	0.001	0.16	0.16	0.16	Leaf scattering coefficient for PAR (-).
`alpar_io`	0.0005	0.1	0.1	0.1	Leaf reflection coefficient for PAR (-).
`beta2`	0.9	0.93	0.93	0.93	Coupling coefficient for co-limitation in photosynthesis model (-).
`co2_mmr`	0.0005	0.00053	0.00053	0.00053	Concentration of atmospheric CO$_2$, expressed as a mass mixing ratio.

Table 3. JULES parameters used to represent vegetation at FIFE site 4439, which vary across runs. These parameters are all specified in the `JULES_PFTPARM` namelist apart from `can_rad_mod` (`JULES_VEGETATION`), `co2_mmr` (`JULES_CO2`) and `beta2` (`JULES_SURFACE`).

JULES notation	`tune-leaf` A.g. (default)	varying dq_{crit} a	 b	 c	fit to Medyn model $g_1 = g_1^{fit}/2$	 $g_1 = g_1^{fit}/4$
`dq_crit_io`	0.070	0.048	0.040	0.035	0.057	0.051
`f0_io`	0.53	0.59	0.64	0.68	0.36	0.22

Table 4. Parameter combinations used for the f_0, dq_crit sensitivity sudies.