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Biogeosciences Discussions

Interactive comment on "A data assimilation framework for constraining upscaled cropland carbon flux seasonality and biometry with MODIS" *by* O. Sus et al.

O. Sus et al.

o.sus@creaf.uab.es

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Final response of authors

1) Response to interactive comment by anonymous referee #1

We generally appreciate the recommendations of reviewer #1, and find them very helpful in clarifying model performance and evaluation. In particular, the reviewer requested more information on the crop model (sowing date estimation, crop establishment, phenology) so that the reader is provided with sufficient information about the relative importance of sowing date estimation vs. LAI state estimation. We also acknowledge that the document can be somewhat streamlined, in particular through omitting some of the information added in parenthesis to the text. Moreover, we acknowledge that there are no observational constraints on the regional carbon (C) flux. Regional model results can thus not be validated. Instead, we emphasize the relative differences between point-scale simulations at the Bondville field patch (for which the model has been validated) and regional simulations for the 104 field patches surrounding the flux tower. Our statement that upscaled model C fluxes are "accurate" is not a validated fact but rather a hypothesis. Nonetheless, the assimilation of MODIS data strongly supports this hypothesis. At Bondville, we find that our model is able to reproduce LAI and C flux data with equal to larger accuracy when driven with MODIS-derived instead of reported sowing dates, and especially so after sequential assimilation of MODIS RDVI. The success of this proof of concept lead us to formulating the hypothesis that model fluxes for other field patches within the area are likely to be similarly accurate, and most likely more accurate than simulations driven with sowing dates modelled as a function of climate.

We accommodate all recommendations through the following changes in the text:

General comments:

- Regarding information about the crop model's sensitivity towards phenological parameters: see changes to lines P11144 L2 until P11145 L5 below
- Regarding sowing date control over LAI seasonality: see the following text about new figure on sowing date estimation inserted below, in the caption in this text labelled Figure 1, in revised manuscript to be labelled Figure 3:

  will add the following text in P11148 L13: "Sowing date is a key control of LAI magnitude and seasonality. A model run initialised at the earliest sowing date (DOY = 90) of maize produces a maximum LAI value about twice as large compared to a model run initiated by the end of the plausible range of values (DOY = 170, Figure 3). The timing of these maximum LAI, dependent on sowing date, can be up to 2 months apart. For soybean, maximum LAI is less sensitive to sowing date, but a strong control on seasonality is obvious as well. There is a clear minimum of squared residuals as a function of sowing date for the example maize field patch, whereas a range of sowing dates spanning about 1 week appears plausible for soybean (Figure 3). The example illustrates both the model's sensitivity to sowing dates, and that an optimal sowing date can be determined within an uncertainty range of $\pm$ 3 days.

- Regarding a clearer articulation of the relative importance of sowing date estimation vs state estimation:

  will add the following text in P11156 L2 to L3: "Sequential MODIS DA reduces a bias in estimating growing season C fluxes at Bondville (data not shown). This bias is partly a consequence of running SPAc with modelled instead of reported sowing dates: in contrast to overall seasonality, the magnitude of observed LAI and NEE is then less well reproduced. Using simulated sowing dates in model runs is necessary for capturing the overall observed seasonality, whereas sequential DA is necessary to compensate generic model deficiencies and additional biases introduced. However, understanding ..."

  will remove sentence in P11150 L10 to L12

Specific comments:

P11140 L12: We acknowledge that the term 'variational data assimilation' is not appropriate in this context (which rather refers to 3/4DVAR assimilation techniques) and will thus be replaced by the term 'batch-calibration' in the revised manuscript throughout.

P11140 L13: We will amend the following lines in order to remove parenthesis and repetitive information to shorten the discussion:

- P11140 L12 and L13: parentheses around text will be removed
- P11142 L12 and L13: text in parentheses will be removed

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- P11143 L15 and L16: text in parentheses will be removed
- P11143 L21 to L23: sentence will be changed to: “Half hourly meteorological forcing data for radiation, temperature, wind speed, humidity, and precipitation have been ...”
- P11144 L1 and L2: text in parentheses will be removed
- P11144 L8 and L9: parentheses around text will be removed
- P11145 L14 to L16: “... of 1300 g C m for which modelled SOM C is in equilibrium, an adjusted litter C content of 400 g C m−2 to reflect annual variability in litter C as observed by Verma et al. (2005), and ...”
- P11146 L8 to L10: text in parentheses will be removed
- P11147 L12 to L13: “... sowing date. These sowing dates span a range of day of year (DOY) from 90 to 170, thus encompassing reported usual sowing dates of maize and soybean for Illinois (USDA, 1997).”
- P11147 L18 to L19: parentheses around text will be removed
- P11148 L2: “... estimate is based on ...”
- P11148 L3: “... EC data and produced ...”
- P11148 L17 to L21: “Soybean sowing dates appear better reproduced by MODIS than those of maize, which are generally premature. 100 % sowing progress of maize is often reached by end- April, whereas reported sowing activity often lasts well into May.”
- P11148 L22 to L24: text in parentheses will be removed

- P11149 L21 to L23: “However, maximum ground-observed LAI values are often underestimated by MODIS, e.g. by âĹij 0.5–1 m2 m-2 for maize 2003 and soybean 2005, but note overestimation in 2004.”
- P11151 L3 to L4: parentheses around text will be removed
- P11151 L7: “Averaged over 104 pixels, the annual...”
- P11152 L10 to L12: “Observed cumulative NBP data indicate a net sink of âĹij 211 g C m-2 after five years, however with changing sign so that observations are a mix of source and sink years. Modelled crop rotations...”
- P11154 L6 to L8: “...simultaneously by âĹij 100 g C m−2 , data not shown. MODIS RDVI was used as an independent constraint on crop LAI for finding...”
- P11154 L12 and L13: text in parentheses will be removed
- P11154 L16 to L20: text will be removed, as it is repetition of results section
- P11155 L2 to L3: “...as scale differences between sub-county model data and census district-level observations (Fig. 1a) are prohibitively large.“
- P11155 L11 to L14: first sentence will be removed, second sentence moved to the end of L5
- P11155 L21 and L22: parentheses around text will be removed
- P11155 L24 to L25: text in parentheses will be removed
- P11155 L25 to L28: last sentence will be removed
- P11156 L4: parentheses around text will be removed

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- P11157 L3 to L6: “Our results confirm previous findings that MODIS data contain enough useful information for correcting some deficiencies in global BGCMs, such as a âĹij 40 % reduction of RMSE in modelled agricultural C fluxes and improved estimated GSL (Demarty et al., 2007).”
- P11157 L9 to L11: sentence will be removed due to repetition
- P11157 L22 to L23: text in parentheses will be removed
- P11158 L3 to L4: text in parentheses will be removed
- P11158 L24 to L25: parentheses around text will be removed
- P11158 L29: text in parentheses will be removed
- P11159 L4 and L5: text in parentheses will be removed
- P11159 L22: “...applications such as for the conterminous US could...”
- P11160 L8: “Here, assuming measured Bondville C budget is spatially representative, observed growing...”
- P11160 L12: “...value, with a deviation of now âĹij 110 to 220 g C m -2.”
- P11160 L13 and L14: parentheses around text will be removed
- P11160 L26 to L28: sentence will be removed
- P11161 L5 to L7: “The observations analysed provide no clear constraints on the sign of NBP, and generic uncertainties in EC data have been documented (Anthoni et al., 2004; Falge et al., 2001). The role of...”
- P11161 L23 to L25: “MODIS RDVI data were assimilated both for the batch-calibration of sowing dates and for improved model state estimation using the EnKF.“

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- P11162 L20: "...dates as observed here in 2002 add..."
- P11162 L23: parentheses around text will be removed

P11140 L14: We acknowledge that due to the lack of regional constraints we cannot refer to our model results as being accurate. Referring to this line and other lines in the text:

- P11140 L14: will be rephrased to: "In doing so, we are able to quantify..."
- P11140 L19: Here we are referring to point-scale simulations at Bondville. As the validation through observations shows, batch-calibration of sowing dates allows for accurate simulations at Bondville. We thus expect this framework to allow for accurate simulations at sites for which ground-truth data are not available, even though we cannot validate this hypothesis with the data available for this study. To make this statement more clear the line will now read: "Validation at the Bondville site shows that growing season C cycling is simulated accurately with MODIS-derived sowing dates, and we expect that this framework allows for accurate simulations of C cycling at locations for which ground-truth data are not available. Thus, this framework..."
- P11161 L21: "accurate" will be deleted
- P11161 L27: "...and allow for accurate simulations..." will be rephrased to "...and thus will probably allow for more accurate simulations..."
- P11162 L5: "accurately" will be deleted

P11141 L23: Agreed, since EC measurements now exist for more than a decade. "Novel" will be deleted.

P11142 L3: Reference will be added.

P11142 L24: We defined a field patch size of 500 m x 500 m as “sufficient”. Within that safety margin, neighbouring effects are minimal when considering variable centre pixel locations (which can be anywhere within a 250 m MODIS pixel time series) and viewing geometry leading to distortions of the sensor’s inner field of view. Those distortions are further minimised in our study through only using data with a viewing angle of $< 40°$. Line will be rephrased as follows: “...sufficient size of 500 m x 500 m surrounding...”

P11143 L12: Site description from P11143 L3-7 will be moved to the beginning of P11142 L12.

P11144 L 23: The references article solely describes the C mass balance model. The reviewer is correct that in the article cited SPA is not yet coupled to the C mass balance model. Line will be rephrased: “A C mass balance model as described in Williams et al. 2005 has been added to SPA, and...”

P11144 L2 until P11145 L5 will be amended as following:

“Moreover, a crop C partitioning scheme and a developmental model have been added (SPA version 2 – Crop Sus et al., 2010, hereafter referred to as SPAc). The C partitioning scheme is based on empirical values of field crop growth analyses (Penning de Vries et al., 1989), and is a function of crop developmental stage (DS). The model representation of DS is introduced into SPAc by a new state variable, varying between 0 at emergence, 1 at flowering, and 2 at maturity. The duration of the phase between sowing and emergence is calculated through thermal time, and lasts typically around 1 week. The progression of DS is based on non-linear functions for temperature f(T) and photoperiod f(P), with $0 < f(T, P) < 1$ (Streck et al., 2008; Sus et al., 2010; Setiyono et al., 2007). DS is calculated as the sum of daily maximum developmental rate (DRmax) multiplied by f(T) and f(P). For maize, f(T) is the only control on developmental rate throughout the crop’s life cycle within SPAc (Streck et al., 2008). For soybean, crop development is affected by f(T) from sowing to maturity, and by f(P) until DS = 1 (as in Setiyono et al., 2007, but simplified). Based on this development-linked C alloca-

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tion pattern, SPAc simulates the allocation of C to roots, foliage, stems, and storage organs. Around emergence, C gained through photosynthesis is mainly allocated to leaves and roots at approximately equal amounts. However, C allocation begins to favour growth of stems as the crop matures throughout spring (0.3 < DS < 1), until before all assimilated C is allocated to storage organs in the reproductive phase (DS > 1). Leaf senescence for both crops is calculated as the bigger value of leaf senescence rate due to mutual shading (SRsh, if LAI > 5) and leaf senescence rate as a function of physiological maturity or age (SRage , if DS > 1, van Laar et al., 1997). We set SRage to increase exponentially with DS, and 50% of senesced C mass is reallocated to storage organs. SPAc sensitivity to parameters controlling crop establishment and development has been analysed for cereal crops in Sus et al. (2010). Considerably small changes in cumulative NEE were found for a 25% change in model parameters controlling timing of emergence (<0.1 % change in cumulative NEE), critical LAI beyond which self-shading senescence is triggered (<5 %), and maximum senescence rate due to self-shading (<1 %). SPAc is particularly sensitive towards changes in DRmax (<20 %), and temperature (<29 %) and photoperiod (<30 %) developmental parameters."

P11146 L6: We will insert: "Next to vegetation indices, these MODIS data products also contain the red and NIR reflectance values themselves."

P11147 L11: Will add in L13: "We expect that the application of uniform meteorology over the study area has negligible effects on model performance regarding spatially continuous climate variables such as temperature and vapour pressure deficit. However, the spatial distribution of precipitation is not accounted for. Modelled field patches are located less than ∼16 km away from the flux tower, and so their water balance is subjected to manageable uncertainty."

P11147 L14: We appreciate that comment, and suggest to include the attached figure in the revised manuscript. Figure caption: Left panels: Model LAI curves are shown for maize (top) and soybean (bottom) and 5 different sowing dates (DOY 90, 110, 130, 150, 170, black lines) for one study area example field patch. MODIS LAI values are shown as grey dots. Model LAI with lowest squared residuals is shown as coloured line. Right panels: Squared residuals between model LAI and MODIS LAI for each of the 80 sowing dates and maize (top) and soybean (bottom). The coloured dot depicts the lowest squared residuals value.

P11147 L16: We will insert "over the entire calendar year".

P11147 L24: As there is a linear relationship between LAI and foliar C in the model, any update on model LAI through assimilation of MODIS LAI had an impact of similar magnitude on foliar C. However, this correction on foliar C, brought about through EnKF updates of the covariance matrix, has no further consequences on model behaviour, as it is LAI that is used for estimating GPP. We also observed updates in root C mass, but to a somewhat smaller extent. Any changes in root C mass have impacts on plant hydraulics and thus water uptake. That means that for some field patches sensitivity to drought was altered, but we observed no significant effects on carbon cycling here. The consequences of changing plant hydraulics on stomatal opening and thus photosynthesis are of second order importance compared to the significant updates of LAI. Stem and storage organ C mass showed only slight to moderate updates, and are not physiologically integrated into the model.

P11148 L3: We used the temporal separation approach, where we defined any differences in MODIS values that are < 4 days apart as data uncertainty originating from various sources such as sensor calibration and atmospheric conditions. This is analogous to the Hollinger and Richardson approach for NEE flux data analysing histograms of residuals between flux data pairs of successive days, and provides us with a final estimate that is within the range of independently determined uncertainties for the NDVI and EVI. We will include the following sentence into the manuscript for clarification (replacing P11148 L2 to L6): "We used the temporal separation approach (Hollinger and Richardson, 2005) to estimate RDVI uncertainty, defining any differences in MODIS values that are < 4 days apart as data uncertainty originating from various sources such as sensor calibration and atmospheric conditions. This approach produced an uncertainty value of ±0.017 s.d. for the RDVI, which is comparable to the MODIS Land Discipline Team (MODLAND, http://modis-land.gsfc.nasa.gov/) values for the NDVI (±0.025) and EVI (±0.015).”

P11150 L2 and L15: We will correct the sentence in L15 as following: “MODIS DA appears generally useful to correct for model deficiencies during growing seasons, but the informational content about fallow season C3 grass growth and C assimilation needs further validation.”

P11153 L11: We agree with the reviewer and will clarify this statement by replacing “However, ...” in L10 with “As expected, ...”

P11154 L13: The timing and rate of simulated senescence is premature and still needs improvement. Using only MODIS LAI data during the vegetative phase will improve model match with observations during that phase. However, model goodness-of-fit during the reproductive phase strongly depends on the model’s simplified senescence algorithm. The batch-calibration procedure of sowing dates will thus be insensitive to late season model values. Consequently, it will not compensate for any weaknesses in simulating senescence by adjusting sowing date to optimise early and late season LAI simultaneously. We expect that in some but not all cases this will lead to a better estimation of sowing date, but premature senescence. Thus, sowing date estimation (the batch-calibration) has consequences on the performance of MODIS DA by the EnKF (the sequential approach), as premature senescence means that model LAI has already fallen to 0 whilst MODIS is still “viewing” a green crop. We will clarify this statement by inserting “sequential” in L14 before “DA procedure”.

P11154 L25: We will rephrase the sentence for clarification as follows: “As modelled sowing dates are mostly premature, we conclude that forward mode maize green biomass is probably underestimated. In other words, a negative model bias in LAI is compensated by an earlier start of the growing season.”

P11155 L1: Even though the absence of a delay in maize sowing date is somewhat surprising, we think that this does not prevent a discussion of the differences in model performance between the two crops. Firstly, the NASS data do not allow for a validation of modelled sowing date. Secondly, Bondville reported sowing dates for maize are always within the range of model values in 2001, 2003, and 2005, and thus seem at least plausible. Thirdly, it is well possible that maize sowing in 2002 could still progress within the usual time window before weather conditions deteriorated, which then were only detrimental for the sowing of soybean that is generally reported to be sown 1-2 weeks later. According to our simulations, maize sowing was finished well before soybean sowing progress could even reach 20 % of crops sown.

P11155 L14: We agree with the reviewer's suggestion and will change the sentence as following in L14 to L15: "..., spatially resolved data for validation."

P11156 L1: In this sentence MODIS DA stands for both sowing date optimization and state adjustment with the EnKF. We acknowledge however that the use of the words "MODIS DA" within the manuscript mostly refers to sequential assimilation of MODIS data. To make the distinction between MODIS DA through batch-calibration and sequential assimilation through the EnKF more clear, we suggest the following changes:

- P11147 L23: "For this study we chose, next to batch-calibration of sowing dates, the EnKF approach for model state estimation as such a DA technique (Evensen ..."
- P11149 L8: "Proof of concept – sequential assimilation . . ."
- P11149 L13: "(no sequential DA)
- P11149 L9 + L14 + L15: "sequential MODIS DA"
- P11149 L25: "The sequential assimilation..."

- P11149 L28: “Modelled LAI is now generally...”
- P11150 L3: “Sequential DA successfully...”
- P11150 L8 + L9: “Model bias is reduced through sequential DA...”
- P11150 L11 + L12: “through sequential MODIS DA”
- P11150 L15: “Sequential MODIS DA...”
- P11151 L2 “...sequential MODIS DA...”
- P11151 L5: “...after sequential MODIS DA”
- P11154 L12: “MODIS data of the vegetative...”
- P11154 L14: “of our sequential DA procedure...”
- P11156 L1: “through sequential MODIS DA”
- P11156 L7: “and sequential DA brought”
- P11156 L16: “reduces sequential MODIS DA”
- P11157 L8: “..., and their influence”
- P11159 L6: ”through the sequential assimilation of...”

P11156 L28: Sentences will be changed to: “Certain model deficiencies remain unresolved after DA. SPAc simulations are less reliable for yield than NEE and LAI, and improvements in representing yield formation are warranted for further study. As Dente et al. (2008) show, considerable improvements can be expected through DA. Nonetheless, we are confident...”

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P11158 L9: We agree with the reviewer and will remove "as they probably would be measured by a tall tower EC system with a footprint area covering a multitude of field patches"

2) Response to interactive comment by anonymous referee #2

We thank referee #2 for her/his comments on our paper. We agree that data assimilation techniques are particularly useful in upscaled crop modelling, for which important model information is difficult to acquire. Uncertain crop models can only benefit from the assimilation of satellite data, despite of their own inherent uncertainties.

P11142 L9 + L10: we will cite Hansen et al. (2007) here.

P11142 L11: The study that the reviewer refers to attempts to provide spatial estimates of cropland carbon cycling. The authors calculate this spatial distribution by means of inventory data and MODIS land cover data. Thus, no mechanistic crop model has been applied, and consequently no MODIS data were assimilated. The study provides an interesting alternative estimate of carbon budgeting at high spatial resolution, but produces only one value per year and location. The temporal dynamics of cropland carbon exchange, and thus their phenology and seasonality, were not assessed, which we see to be a key element of our study. Moreover, to our knowledge this is the only study so far in which the upscaled seasonality of cropland carbon fluxes has been simulated in such detail by assimilating MODIS data in two different ways. Our estimates of sowing dates and LAI development are strongly driven by observational constraints, and simulated NEE is thus, regarding its degree of realism of phenology, a novel product. For completeness, we will insert at L13: "In a recent study (West et al., 2010), cropland inventory data were combined with the MODIS land cover product to calculate spatially resolved estimates of C budgeting for the conterminous U.S.A. However, as no mechanistic crop model has been applied and consequently no MODIS data were assimilated, the authors could not provide estimates of the seasonality of upscaled C fluxes."

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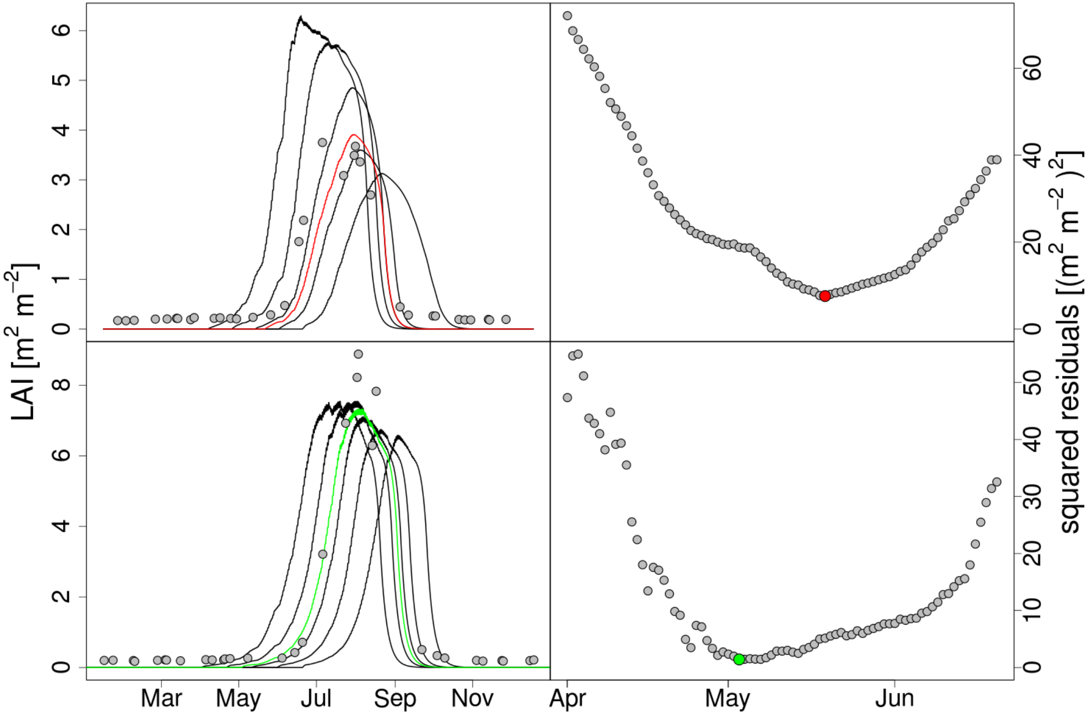

Fig. 1. Caption does not fit here. See comment at P11147 L14 in manuscript.