Answer to Referee #1

Answer to comments from the reviewer.

Comments from the reviewer were left intentionally in this document and written in roman font. Our answers are written in italics.

General comments

Recently, there was a debate on Science (van Groenigen et al., 2014) and Global Change Biology (van Groenigen et al., 2015; Georgiou et al., 2015) about how to represent priming effect in large-scale CENTURY type decomposition models. In this regard, Guenet et al. presented a timely and important study, which offer a simple way to include priming effect in large-scale land surface models. In addition, it's good to see that the proposed PRIM model was evaluated against multiple datasets.

However, writing was a little weak in terms of conciseness and smooth, please check my details comments, I listed some issues, author should carefully refine the paper on their own, I believe you will find more.

I have two major concerns, the first one may be out of the scope of PRIM, but it is important in terms of modeling priming effect. I am not asking the author to modify PRIM accordingly, but more discussions are definitely needed.

Major comments

1. Priming effects is related to nitrogen availability. Why choose ORCHIDEE not O-CN?

The priming effect is closely related to soil nutrient availability. Both positive and negative priming have been observed when soil N is limited. Basically, there are two prevailing N-centric priming hypotheses (1) when N availability is low, microbes use fresh carbon to mine old carbon and obtain nitrogen, leading to a positive priming effect;

(2) when N availability is strongly limited, adding fresh carbon enhance competition between roots and microbes, consequently reduce microbial activity and depress microbial growth.

It is interesting to see how PRIM work with O-CN. In some sense, I would argue that the priming effect modeling must consider nitrogen, because that is the theoretically "correct" way and supported by large amount of priming observations. But having priming effect coded in carbon only model is a good start. Considering nitrogen in PRIM will be a big plus. The author should have more discuss on this issue including existing theories and observations, potential model development.

We fully agree with this remark and we are of course aware the N availability is a major driver of priming effect, nevertheless we decide to start without N to simplify the approach and make the model outputs easiest to understand. Moreover, take into account nitrogen would have probably induced to define the c parameter of eq. (1) to (3) as a function of mineral N and it that case we would need soil incubations detailing the mineral N dynamic to define the equations parameters. Such information is generally not fully available in the *priming effect incubations experiments we used to optimize the PRIM parameters reducing drastically the data available to define the model parameter.*

We add some comments in the conclusion section related to this point.

"The role of N in the priming intensity as well as the extra N mineralization induced by priming and its effect on primary production may represent the next addition to the soil representation in a land surface model by adding a control on the c parameter depending on the mineral N availability and on the C:N ratio of the considered pool. Nevertheless, some detailed information on the N dynamic in priming effect experiments would be necessary to do so and very few authors reported the impact of priming effect on N dynamic after FOC additions."

2. About model core assumption

The most attractive part of PRIM is that it does not require explicitly microbial dynamics (e.g., microbial biomass), by assuming microbial biomass is always equilibrium with FOC. Such assumption is suitable in terms of simplicity, but is it suitable for model predictability? What's the theoretical basis of this assumption? What's the potential bias by imposing this assumption? Please have more discussion, because this assumption is the backbone of this study.

This assumption is based on the rapid response of soil microorganisms to changes in their environment (Lundquist et al., 1999). The microbial turnover has been observed to be of few days (Schmidt et al., 2007). In particular, in priming effect studies based on soil incubations, the soil microbial biomass is already at equilibrium after few days (Fontaine et al., 2004 for instance). The time step of the soil module is daily, we therefore considered this assumption as acceptable regarding the simplicity it gives to the equations.

The potential bias we may face by imposing this assumption would be to over(under)estimate the priming intensity in particular when FOC inputs reduce (increase) drastically from one day to another (after fires or harvests for instance). Indeed, after harvest a substantial amount of aboveground material may be added to the soil and if microbial biomass is not at equilibrium during the time step considered but need few days to reach its equilibrium value, the priming effect intensity might be overestimated during these few days.

Fontaine, S. et al. Mechanisms of the Priming Effect in a Savannah Soil Amended with Cellulose. Soil Sci. Soc. Am. J. ***68,*** *125 (2004).*

Lundquist, E. ., Scow, K. ., Jackson, L. ., Uesugi, S. . & Johnson, C. . Rapid response of soil microbial communities from conventional, low input, and organic farming systems to a wet/dry cycle. Soil Biol. Biochem. ***31,*** *1661–1675 (1999).*

Schmidt, S. K. et al. Biogeochemical consequences of rapid microbial turnover and seasonal succession in soil. Ecology ***88,*** *1379–1385 (2007).*

Specific comments

1. Title: better not use such a detail version number, first of all people who do not work on ORCHIDEE would not care about the version, secondly you can put the details in other section (such as your code availability section), but not in title.

This is imposed by the Journal please see the editor comment.

2. P9198. L18-19. Be concise: "the soil carbon model structure of ORCHIDEE land biosphere model" -> "ORCHIDEE soil decomposition model"

This was corrected in the new version.

3. P9198. L21-23. Sentence doesn't make sense. Rewrite it. How about "SOC decomposition is modulated by soil temperature and moisture functions. Active SOC decomposition is further modulated by a clay function. These functions are the same as in CENTURY."

This was corrected in the new version.

4. P9199. L3. that simulate a priming effect -> to simulate priming effect

This was corrected in the new version.

5. P9199. Eqn 1-3. SOCLabile , please be consistent throughout the paper. Either use labile SOC or active SOC. It's confusing to have both active SOC and labile SOC meaning the same thing.

This was corrected in the new version.

6. P9199. Eqn. 2-4. Does clay function (gamma) only affect active SOC pool?

Yes, we did a mistake in the equation. We corrected in the new version.

7. P9199. L11. FOC, first time used in materials and methods section, better to have a full name.

This was corrected in the new version.

8. P9199. L22-23. Be concise, “assume instead a linear relationship between microbial biomass and FOC. Thus, it implicitly assumes that MB is always in equilibrium with FOC” -> “assumes that MB equilibrates with FOC thus the relationship between MB and FOC is linear”

This was corrected in the new version.

9. P9200. L2. The decomposition model runs at a daily time step. duplicated statement with 9199 Line 1, remove it.

This was corrected in the new version.

10. P9200. L13. “very different situations” What are these situations? elevated CO2? warming? dry/wet?

We rephrase to clarify this statement

11. P9200. L15. “three different models” -> “three different sub-models”.

This was corrected in the new version.

12. P9200. L19. “manage the aspects related to” -> “deal with”

This was corrected in the new version.

13. P9200. L24. “describe” -> “classify”

This was corrected in the new version.

14. P9201. L8. priming effect was measured

This was corrected in the new version.

15. P9201. L9. “by comparison with a control without FOC” -> do you mean “by comparing a control study without FOC with a perturbation study with FOC”?

This was corrected in the new version.

16. P9202. L8-10. I don’t fully understand. Did you run run ORCHIDEE-PRIM to get equilibrium carbon states? If you run ORCHIDEE till equilibrium and use ORCHIDEE-PRIM to run transient, SOC pools are out of equilibrium at the beginning of the simulations.

We agree that this is a drawback of the study but because we need the fraction of each pool to initiate the parameterization of PRIM we were not able to run ORCHIDEE-PRIM to define the fraction of each pools or with dummy parameters with consequences on the optimization process quite complex to anticipate.

17. P9202. L19-20. how to estimate initial fraction of each pool with location formation?

To run ORCHIDEE for each sites we needed the coordinates to extract the necessary boundaries conditions. Therefore, without it was impossible to run the model. We rephrase to clarify.

18. P9203. L13-14. Be concise: “turnover rate (kSOC) for each of the three pools as well as the priming parameter c of Eqs. (1), (2) and (3) specific of each pool” -> “turnover rate (kSOC) and priming parameters c for each of the three pools”

This was corrected in the new version.

19. P9203. L21. “use all data streams assimilated” -> “assimilating all data streams”

This was corrected in the new version.

20. P9204. L10. How do you calculate J(x) gradient? By finite difference method? adjoint method?

We used the finite difference method. We added this information in the ms.

21. P9204. L24. “only too studies” -> “only two studies”

This was corrected in the new version.

22. P9204. L25. No covariance between c and k? Intuitively, should active C pool have faster turnover time as well as get easily primed (high substrate quality and easily get attacked by extracellular enzyme)?

Actually, it seems that the more recalcitrant pools are most sensitive to priming (Fontaine et al., 2007, Guenet et al., 2012). But the c parameter values depend on the pool considered and have different values.

Fontaine, S. et al. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. Nature ***450,*** *277–280 (2007).*

Guenet, B., Juarez, S., Bardoux, G., Luc, A. & Claire, C. Evidence that stable C is as vulnerable to priming effect as is more labile C in soil. Soil Biol. Biochem. 43–48 (2012). doi:10.1016/j.soilbio.2012.04.001

23. P9205. L11-14. I’m confusing.

(1) Did you use observed total SOC, but simulated fraction. Any motivation? (2) is this fraction important in terms of controlling priming effect, my guess is positive. (3) you can easily do a sensitivity analysis by varying the fractions

Indeed we used observed total SOC but simulated fractions because i) we had not enough information on the inputs, on the soil temperature and moisture to run the model until equilibrium and ii) the pools defined in our model are not measurable so we had no other solution that using the simulated fraction and distribute the total SOC amount within the simulated fractions.

24. P9206. L5. Same proportion. Why use proportion not absolute amount?

We used proportion because in the papers we used to evaluate the model the treatments are presented as proportion (no above ground inputs, control and doubled above ground inputs). Therefore, we decided to used proportion to follow the same approach and thus be able to compare the observed priming and the calculated priming. Moreover, to use absolute amounts we would had need a high temporal resolution description of the primary production on site (to be able to force the model at each time step) and this information was not available.

25. P9207. L15. why the uncertainty of slow pool is so tiny compared with active and passive pool. Looks like this parameters is perfectly constrained (tiny posterior error)?

The slow pool is always the biggest pool and since the CO_2 *flux is controlled by the pool size, it is also the main contributor to the flux. Consequently, the optimization procedure mainly act on this parameter to fit the data.*

26. P9207. L21-22. If original ORCHIDEE succeeded, then what's the value of introducing PRIM.

It is not surprising that when we evaluate both models on the dataset used for optimization they performed well but in the following lines we clearly show that when using other datasets (like the control incubations or even more independent data), the incorporation of priming clearly improve the model performances.

27. P9208. L11-13. PRIM works pretty bad. Any comments? Why? How to improve it?

As discussed above, priming is a complex phenomenon resulting from the interactions of different mechanisms (co-metabolism, N mining, competition for a substrate between different microbial groups) that we summarized in a very simple equation. Therefore it is not that surprising that we are not able to fully catch all the variability observed. We added some text related to this comment in the new version.

"Furthermore, PRIM was not able to fully catch the observed variability of priming. As discussed above, priming is a complex phenomenon resulting from the interactions of different mechanisms that we summarized in a very simple equation. Therefore, PRIM is probably good in representing a general trends but not all the complexity of the phenomenon."

References

Georgiou, Katerina, et al. "Towards improved model structures for analyzing priming: potential pitfalls of using bulk turnover time." Global change biology(2015).

van Groenigen, Kees Jan, et al. "Application of a two pool model to soil carbon dynamics under elevated CO2." Global change biology (2015).

van Groenigen, Kees Jan, et al. "Faster decomposition under increased atmospheric CO2 limits soil carbon storage." Science 344.6183 (2014): 508-509

Answer to Referee #2

General comments: The MS by Guenet et al., "Towards a representation of priming on soil carbon decomposition in the global land biosphere model ORCHIDEE (version 1.9.5.2)" describes the attempt to model priming effect at ecosystem scale using the CENTURY-type ORCHIDEE model with new features (and three additional parameters). I admit that SOM matter turnover models should be developed in this direction and I welcome this attempt. This work is also in general trend of microbial-driven model application for global SOM simulation (e.g. Li et al.,2014, Wieder et al., 2014, 2015). The strong side of the work is a thorough model calibration and validation against independent datasets including both laboratory incubation experiments and field observations. All mathematical and statistical procedures as well as experimental data taken from literature are carefully described. My main concern is that authors try to improve the SOM model from previous generation (CENTURY-type, based on first order kinetics) keeping the original cumbersome and complex structure. Including the interactions between pools could help to simplify the model structure, but this was not done.

We choose to keep the original CENTURY-type structure because it is now well known that several pools are necessary to reproduce long-term SOC dynamic. Of course we may change totally the definition of the pools to have more easily measurable pools (physically-protected C, height molecular weight compounds, DOC, etc.) but this would need a more data to parameterize the model. Moreover, the difference between both models would have been more complex to understand, in particular to disentangle the effect of the new decomposition scheme and the effect of the new structure. We considered this action as a second step that we are currently doing.

Therefore, the results are not very impressive: authors show that ORCHIDEE-PRIM hardly improve the prediction of CO2 production in litter amendment experiments and addition of new parameters increase Bayesian Information Criterion in many cases, when original model is compared with modified one, i.e. PRIM model is overparameterized. Authors have to describe better the advantages of their approach, which is based on well-tested and broadly used ORCHIDEE model.

Indeed, as a first guess, the results does not look very impressive but as mention in the discussion section ORCHIDEE and ORCHIDEE-PRIM share the same vegetation module and we were not able to split the observed soil CO_2 flux into roots respiration and heterotrophic respiration. Nevertheless, when PRIM and the standard soil module are evaluate independently from the vegetation module and using independent data from the ones *used to optimize the model the performance are much better with PRIM. We complete the discussion in the new version to better explain why the new approach is interesting.*

"Nevertheless, when using independent soil incubations data from the one used to optimize the model the improvement is quite clear with BIC values much lower with PRIM than with the standard soil module (347.4 and 546.2, respectively)."

The capability to describe priming effect is an important improvement, but this can be done explicitly with a help of a simple models and this kind of models already was applied for global scale (see review by Wieder et al, 2015). If direct comparison of new generation model with explicit description of microbial biomass turnover is not possible, you should at least mention alternative approaches and discuss pro and contra of their application in relation to your approach.

We do not totally agree with this statement. Some attempts were done to applied microbial explicit model at global scale but they generally used plants inputs as a boundary condition (Wieder et al., 2014, for instance). In Wieder et al., 2015, the 13 models presented in the table 1 are generally not applied at large scales. Nevertheless, it is interesting to discuss how our approach may facilitate the challenge of integrating microbial explicit models in ESMs.

"Finally, the use of microbial steady state model like ORCHIDEE-PRIM present several advantages compared to explicit microbial models. Wieder et al., (2015) identified several challenges related to the incorporation of explicit microbial models in ESMs. In particular, it may induce unrealistic temporal oscillations in response to small perturbations and it needs much more parameter than the classical approach. With ORCHIDEE-PRIM these two difficulties are resolved since we only add three more parameters and because the model is not subject to short-term oscillations."

Some further specific and technical comments are below:

Discussion section: I find it reasonable to discuss the levels of complexity allowing to present priming effect in the models, similar to way as it was done in paper by Wutzler and Reichstein (2013). PRIM model according to their classification can be described as microbial steady-state model, also according to you description at P9199L23.

We discussed the model complexity in more details in the new version.

"The PRIM soil model, which is a microbial steady-state model, might not be able to reproduce short-term response to abrupt change of FOC inputs but with negligible bias over the long term (Wutzler and Reichstein 2013). However, it might have similar performances

than more complex models to reproduce long-term trends of FOC inputs (Wutzler and Reichstein 2013).”

P9195 L21 - reference Luo et al is absent in the list.

The reference was added.

P9196 L3-4. Interestingly, that you cite paper by Kemmit et al., 2008 in support of your claim that soil decomposers are the main actors of SOC decomposition. In fact, in the cited paper authors try to prove the idea that microbial biomass size, composition or specific activity do not influence the decomposition - i.e. opinion completely opposite to your statement.

Indeed the sentence we written was a bit awkward. We corrected in the new version.

“The first order kinetics used in most models obviates the role that microbial decomposers are known to play in controlling SOC mineralization (Cleveland et al., 2007; Garcia-Pausas and Paterson 2011), but their activities is controlled by physical and chemical drivers (Kemmit et al., 2008).”

P9197 L16: Expression is not clear "several of parameters" what do you mean with this?

We modified the sentence.

“Several mechanisms may be involved in controlling priming (Fontaine et al., 2003; Blagodatskaya and Kuzyakov 2008, Guenet et al., 2010b), and conceptual models of priming can have substantial number of parameters making their parameterization quite complex at large scales (Wutzler and Reichstein, 2013).”

P9198 L24 ..the same as..

This was corrected in the new version

P9201 L9-12: What was a basic underlying principle for the selection of data for model calibration? You sometimes take one treatment or incubation or variant among several published datasets.

We clarified this aspect:

"Finally, several treatments might be performed in the studies used to optimize the model (different soils, different types and amount of FOC). When the treatments performed differed on aspects reproducible by the model (amounts of FOC added, different clay content in the soils used, etc.) we considered all the treatments. In the opposite case we averaged the results of the different treatments to perform the optimization except in case where the treatments clearly impact the results without the possibility to reproduce the experimental design with the model (addition of mineral N for instance)."

P9202 L6 correct misprint.

Done in the new version

P9203 L10: Please, describe how these two fraction of respiration flux were separated. Was root respiration the same for litter amendment and litter exclusion variants?

The two fluxes were not separated on the field experiments introducing difficulties to evaluate the full ORCHIDEE and ORCHIDEE-PRIM models since they only differ in their SOC decomposition schemes. We clarified this point in the new version.

"The data measured at field scale are the soil CO2 efflux including the heterotrophic respiration but also root respiration in the same flux without clear separation of the two components."

Figure 2 and 3: Please indicate (as in text) that Figure 2 present result of model calibration (dataset 2.2.1) and Fig. 3 present the result of model evaluation on independent dataset (2.2.2).

We modified the figure captions.

"Figure 2: Scatter plot between data and the PRIM model outputs for the incubations with FOC amendment (a), without FOC amendment (b) and for priming effect (c). The dataset used here are the similar to those used for optimization (a) or are the control incubations (b) and are described in section (2.2.1). Red lines indicate the 1:1 line. Different symbol indicate different studies.

Figure 3: Scatter plot between independent data from optimization (dataset describes in section 2.2.2) and the soil module of ORCHIDEE outputs (a) or between data and the PRIM model outputs (b). Red lines indicate the 1:1 line."

References:

Li J, Wang G, Allison S, Mayes M, Luo Y. 2014. Soil carbon sensitivity to temperature and carbon use efficiency compared across microbial-ecosystem models of varying complexity. Biogeochemistry 119 (1-3):67-84.

Wieder WR, Allison SD, Davidson EA, Georgiou K, Hararuk O, He Y, Hopkins F, Luo Y, Smith MJ, Sulman B et al. . 2015. Explicitly representing soil microbial processes in Earth system models. Global Biogeochemical Cycles: DOI: 10.1002/2015GB005188

Wieder WR, Bonan GB, Allison SD. 2013. Global soil carbon projections are improved by modelling microbial processes. Nature Clim. Change 3 (10):909-912.

Wutzler T, Reichstein M. 2013. Priming and substrate quality interactions in soil organic matter models. Biogeosciences 10(3):2089-2103.

Towards a representation of priming on soil carbon decomposition in the global land biosphere model ORCHIDEE (version 1.9.5.2).

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Abstract

Priming of soil carbon decomposition encompasses different processes through which the decomposition of native (already present) soil organic matter is amplified through the addition of new organic matter, with new inputs typically being more labile than the native soil organic matter. Evidence for priming comes from laboratory and field experiments, but to date there is no estimate of its impact at global scale and under the current anthropogenic perturbation of the carbon cycle. Current soil carbon decomposition models do not include priming mechanisms, thereby introducing uncertainty when extrapolating short-term local observations to ecosystem and regional to global scale. In this study we present a simple conceptual model of decomposition priming, called PRIM, able to reproduce laboratory (incubation) and field (litter manipulation) priming experiments. Parameters for this model were first optimized against data from 20 soil incubation experiments using a Bayesian framework. The optimized parameter values were evaluated against another set of soil incubation data independent from the ones used for calibration and the PRIM model reproduced the soil incubations data better than the original, CENTURY-type soil decomposition model, whose decomposition equations are based only on first order kinetics. We then compared the PRIM model and the standard first order decay model incorporated into the global land biosphere model ORCHIDEE. A test of both models was performed at ecosystem scale using litter manipulation experiments from 5 sites. Although both versions were equally able to reproduce observed decay rates of litter, only ORCHIDEE-PRIM could simulate the observed priming (R^2=0.54) in cases where litter was added or removed. This result suggests that a conceptually simple and numerically tractable representation of priming adapted to global models is able to capture the sign and magnitude of the priming of litter and soil organic matter.

Keywords: soil carbon decomposition, global land biosphere model, priming effect, climate change.

1. Introduction

Soils are the largest reservoir of organic carbon (C) on land, holding three times as much as plant biomass globally (MEA, 2005). The dynamics of long-term soil organic matter formation (Schmidt et al., 2011) and its decomposition on time scales of future climate change (Jones et al. 2003) both remain poorly understood. The lack of a mechanistic understanding of soil carbon dynamics on time scales going from years to centuries induces important differences in the future projections of the global land carbon storage among global land biosphere models (Todd-Brown et al., 2013).

Different conceptual models have been proposed to explain empirical data on soil carbon decomposition, mainly incubation experiments (Wutzler and Reichstein, 2008; Manzoni and Porporato, 2009). Those conceptual models are usually calibrated to fit data (i.e. measurements of stock evolution or fluxes) from experiments on soil incubation, and on time scales going from hours to days (Panikov and Sizova, 1996; Blagodatsky and Richter 1998). It was shown by Wutzler and Reichstein (2008) that conceptual decomposition models accounting for interactions between labile and more recalcitrant microbial-related carbon, often called “priming effects”, could better fit data from incubation experiments acquired over periods of about 100 days.

The conceptual models of soil carbon decomposition encapsulated in global land biosphere models usually ignore interactions between labile and recalcitrant carbon. All global land biosphere models part of the Earth System Models used for IPCC climate projections are based on donor-pool dominant transfer and first order decay (Luo et al. 2015). Many of those global land biosphere models have soil carbon modules derived from the CENTURY (Parton et al., 1988) and RothC (Coleman and Jenkinson, 1999) models, in which the first order decay rates of different pools are modulated by soil temperature and moisture, as well as by soil texture (Friedlingstein et al., 2006).

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Although the conceptual models with priming showed a more realistic behavior than first order decay models when applied to short term incubation data, one may still wonder if priming significantly influences the dynamics of soil carbon on time scales ranging from years to decades, and at large spatial scales. On the one hand, incorporating priming in a global land biosphere model has the disadvantage of introducing new parameters that are difficult to constrain and of generating a more complex - but unproven - dynamical behavior than the first order decay models. On the other hand, if the performances of first order decay models are not satisfactory at the large scale, structural changes of soil carbon models are needed and must be carefully tested.

The current situation with first-order decay dynamics in global land biosphere is that out of the 11 Earth System models used for the IPCC-AR5 CMIP5 simulations and benchmarked by Todd-Brown et al., (2013) against a global soil organic carbon (SOC) map, only six succeeded in representing the total mean C stocks at the global scale, but all failed to reproduce the spatial heterogeneity of SOC stocks as well as the SOC distribution under different vegetation cover (Todd-Brown et al., 2013). Possible causes of model failure include both errors in model structure but also errors in the different parameters controlling soil carbon dynamics. The optimization of the parameters of a first order decay model against a global SOC map could only partly reduce regional discrepancies with observations, with the optimized model explaining only 41% of the global variability of SOC (Hararuk et al., 2014). On the other hand, the use of a structurally different model that accounted for microbial biomass was shown to produce a rather realistic large-scale SOC variability, but very different soil carbon dynamics in response to future climate change (Wieder et al., 2013). This illustrates that model structure matters a lot for the simulation of the current distribution of soil carbon and its future evolution in response to climate and CO_2 changes.

Discrepancies between global land biosphere model predictions and observations are partially due to models lacking key mechanisms controlling SOC dynamics (Schmidt et al., 2011). One example is the interactions with the N cycle. The majority of the ESMs used for the IPCC-AR5 CMIP5 Earth System simulations did not represent explicitly the nitrogen cycle, but the two ESMs with an explicit nitrogen cycle did not result either in a better simulations of current SOC (Todd-Brown et al., 2013). Another example is the role of microorganisms. The first order kinetics used in most models obviates the role that microbial decomposers are known to play in controlling SOC mineralization (Cleveland et al., 2007; Garcia-Pausas and Paterson 2011), but their activities is controlled by physical and chemical drivers (Kemmit et al., 2008). Therefore, ESMs have significant gaps in reproducing the mechanisms related to microbial dynamics such as priming (see definition below), the object of this study.

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Soil C priming is defined as a modification of SOC decomposition rates when fresh organic C (FOC) is added (Kuzyakov et al., 2000). Priming is almost ubiquitously observed in ecosystem studies where organic matter inputs are altered in laboratory incubations (reviewed by Blagodatskaya and Kuzyakov 2008) or directly on the field (Boone et al., 1998; Borken et al., 2002; Chemidlin-Prévost-Bouré et al., 2010; Subke et al., 2004; Sulzman et al., 2005; Xiao et al., 2015). Priming can occasionally be negative but most commonly has a stimulative effect on the decomposition of organic matter that decomposes. Several mechanisms may be involved in controlling priming (Fontaine et al., 2003; Blagodatskaya and Kuzyakov 2008, Guenet et al., 2010b), and conceptual models of priming can have substantial number of parameters making their parameterization quite complex at large scales (Wutzler and Reichstein, 2013). Wutzler and Reichstein (2008) proposed conceptual models summarized into different equations to introduce priming without using too many parameters, but in all cases an explicit representation of microbial biomass was required. Recently, Guenet et al., (2013a) modified the equation proposed by Wutzler and Reichstein (2008) to represent priming without an explicit representation of microbial biomass, assuming that microbial biomass is always at equilibrium with FOC. This assumption is suitable for being

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incorporated into ESMs since it adds only one more free parameter compared to the first order kinetic models. This priming scheme was incorporated into the global land biosphere model ORCHIDEE, with the priming parameters statistically calibrated to reproduce the same equilibrium state (in terms of C stocks, after spin up of the model) than the standard version based on CENTURY (Guenet et al., 2013b). Despite its calibration ensuring the same initial state of SOC for England and Wales, the version of ORCHIDEE with priming resulted in a loss of SOC during the late 20th Century, in better agreement with inventory data (Bellamy et al., 2005) than the standard version which produced a continuous SOC gain. In that study, however, the parameters of the priming model were not based on observations but tuned instead to equilibrium SOC values. The objectives of this study are therefore:

- To derive optimal parameter values of a priming model (PRIM) with C inputs forced by data by using a Bayesian method (Tarantola, 1987) with priors and data from 20 different soil incubations.
- To introduce the calibrated PRIM model into the ORCHIDEE ecosystem model version AR5 and evaluate the new version ORCHIDEE-PRIM against independent *in situ* litter manipulation experiments at ecosystem scale.
- To assess if the priming model significantly improves the simulation of SOC mineralization compared to the standard first order decay model used in ORCHIDEE, on time scales of months to years.

2. Materials and Methods

The material and methods section is summarized in Fig. 1.

2.1 Models presentation

2.1.1 Soil carbon priming model PRIM

To represent priming, we used the ORCHIDEE soil decomposition module, which is similar to CENTURY (Parton et al., 1988). It has three carbon pools (active, slow and passive) and two litter pools (metabolic and structural). SOC decomposition is modulated by soil temperature and moisture functions. Active SOC decomposition is further modulated by a clay function. These functions are the same as in CENTURY but they are driven by soil physical variables calculated at a daily time step by the soil physics of ORCHIDEE (Krinner et al., 2005). In the PRIM model, we replaced the CENTURY decomposition equations by those developed by Guenet et al. (2013a) to simulate a priming effect:

$$(1)\quad \frac{dSOC_{Active}}{dt} = I - k_{SOC_{Active}} \times SOC \times (1 - e^{-c\times(Litter\_C)}) \times \theta \times \tau \times \gamma$$

$$(2)\quad \frac{dSOC_{Slow}}{dt} = I - k_{SOC_{Slow}} \times SOC \times (1 - e^{-c\times(Litter\_C + SOC_{Active})}) \times \theta \times \tau$$

$$(3)\quad \frac{dSOC_{Passive}}{dt} = I - k_{SOC_{Passive}} \times SOC \times (1 - e^{-c\times(Litter\_C + SOC_{Active} + SOC_{Slow})}) \times \theta \times \tau$$

with I being the input of C into the pool considered, k_{SOC} the SOC decomposition rate for the active, the slow and the passive pool, $Litter\_C$, the sum of all the litter pools of the model. θ, τ, and γ are the soil moisture function, the temperature function and the clay function modulating decomposition, respectively. c is a parameter controlling the impact of the fresh organic carbon (FOC) pool on the SOC mineralization rate. Here, we considered that FOC represents all the carbon from pools more labile than the pool being affected as shown in equation (1) to (3). Therefore, FOC is only litter for the active SOC pool, but for the slow SOC pool, FOC is the sum of the litter and the active SOC pool. Finally, for the passive SOC

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pool, FOC is the litter and the active and slow carbon pools. The decomposition of the first donor litter pool is described using first order kinetics (4):

$$(4)\quad \frac{dLitter\_C}{dt} = I - k_{Litter\_C} \times Litter\_C \times \theta \times \tau$$

In the Wutzler and Reichstein (2008) equation, the SOC mineralization was described by:

$$(5)\quad \frac{dSOC}{dt} = I - k_{SOC} \times SOC \times (1 - e^{-c \times MB})$$

with *MB* being the microbial biomass. Unlike Wutzler and Reichstein (2008), our model does not explicitly simulate *MB* but assumes that MB equilibrates with FOC thus the relationship between MB and FOC is linear. Consequently, we represent priming using a direct relationship between FOC and SOC mineralization. Finally, the moisture, temperature and clay functions are described by equation (6), (7) and (8), respectively with *soil_moisture* in m^3 H_2O m^{-3} of soil, *soil_temperature* in Kelvin and *clay* in %wt :

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$$(6)\quad \theta = \max(0.25, \min(1, -1.1 \times soil\_moisture^2 + 2.4 \times soil\_moisture + 0.29))$$

$$(7)\quad \tau = \exp(0.69 \times (soil\_temperature - 303)/10)$$

$$(8)\quad \gamma = 1 - 0.75 \times clay$$

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2.1.2 ORCHIDEE and ORCHIDEE-PRIM

ORCHIDEE is a process-based global land biosphere model that calculates the fluxes of CO_2, H_2O, and heat between the terrestrial land and the atmosphere. The time step of the model is 1/2-hour, and the variations of H_2O and C pools are calculated on a daily basis. The model has been evaluated at different scales (sites, regions, globes) and under different climates from the tropics to northern boreal zones (Krinner et al., 2005; Ciais et al., 2005;

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Santaren et al., 2007; Piao et al., 2006). ORCHIDEE results from the coupling of three different sub-models. The first one is called SVAT SECHIBA and describes soil water budget and turbulent fluxes of energy and water between the atmosphere and the biosphere (Ducoudré et al., 1993; de Rosnay and Polcher, 1998). The second one is derived from the dynamic global vegetation model LPJ (Sitch et al., 2003) and deals with vegetation dynamics (fire, sapling establishment, light competition, tree mortality, and climatic criteria for the introduction or elimination of plant functional types). The last, called STOMATE (Saclay Toulouse Orsay Model for the Analysis of Terrestrial Ecosystems) deals with phenology and carbon dynamics of the terrestrial biosphere. Twelve plant functional types (PFT) are used to classify the vegetation. Each PFT dynamic is controlled by similar set of governing equations but using different parameter values. Only the leafy season onset and offset, are PFT-specific (Krinner et al., 2005).

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The simulation of SOC in ORCHIDEE version is based on CENTURY (Parton et al., 1988) as described above. No vertical description of the SOC is included in the ORCHIDEE version used here. In ORCHIDEE-PRIM we replaced CENTURY by the PRIM model described in section 2.1.1.

2.2 Data description

2.2.1 Incubation experiments to calibrate the priming model

We optimized the PRIM parameters and the ORCHIDEE soil module parameters using data from soil incubation experiments where FOC was added and the priming effect was measured by comparing a control study without FOC with a perturbation study with FOC (table 1). The data come from 20 incubations (from nine studies) of duration going from one week to 10 months. The incubated soil samples have very different characteristics (table 1) and came from different ecosystems (grassland, cropland, broadleaf forest, needleleaf forest,

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savannah). However, the great majority of the data used to optimize the model were obtained from temperate soils. In the incubation experiments, added FOC was labeled with ^{13}C or ^{14}C and therefore the respired CO_2 fluxes coming from either SOC already present before the FOC amendments or from the FOC induced priming of SOC pools was estimated separately. We used only incubations performed during at least 7 days to eliminate all studies that potentially observed apparent priming effects. Apparent priming is a replacement of the ^{12}C in microbial biomass with labeled carbon isotopes, a short- term artifact due to the amendment of labeled material to an unlabelled soil (Blagodatskaya and Kuzyakov, 2008). Moreover, we used only studies that reported cumulative respired CO_2 fluxes in order to optimize the priming parameters against the extra CO_2 fluxes obtained at the end of the experiment and not those resulting from short-term priming dynamics, since cumulative mineralization integrates the different processes occurring during incubation. Finally, several treatments might be performed in the studies used to optimize the model (different soils, different types and amount of FOC). When the treatments performed differed on aspects reproducible by the model (amounts of FOC added, different clay content in the soils used, etc.) we considered all the treatments. In the opposite case we averaged the results of the different treatments to perform the optimization except in case where the treatments clearly impact the results without the possibility to reproduce the experimental design with the model (addition of mineral N for instance).

We also use the control incubations without FOC amendments to evaluate both models. We extracted data from the figures of original publications (Table 1) using GraphClick version 3.0 . Several input variables are needed to run the soil model, as described in section 2.1.1. When data were not available from the surveyed publications, we obtained them from the databases normally used for running ORCHIDEE, except for the C:N ratio of FOC and for clay content where data came from Rodal et al., (1960) and from USDA (http://soils.usda.gov/technical/classification/osd/index.html.), respectively. The three carbon pools of CENTURY are not measurable (Six et al., 2002), so we cannot estimate how much C of in each pool is present in the incubated samples. To calculate the distribution of C among the three pools of the model we ran ORCHIDEE until equilibrium was reached at the sites where soil samples were taken and calculated the percentage of each pool.

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2.2.2 Incubation data used for evaluation of the priming model

A first evaluation of the soil carbon model with and without priming is performed at the scale of soil samples against independent data from the large database of soil incubations (300 in total) published by Moyano et al., (2012). Within this database we selected the experiments where all the inputs necessary to run the two soil carbon models were available (clay, content, moisture, temperature, SOC content at the beginning of the incubation) and where cumulative mineralization or mineralization rates associated to the time step between two measurements were reported. We removed all the studies without information on the location since geographical coordinates are necessary to run ORCHIDEE and thus estimate the initial fraction of each pool. We selected only data coming from experiments without important soil manipulation (e.g. compaction, litter amendments). The model evaluation was performed against a set of 164 independent incubation experiments.

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2.2.3 Ecosystem-level data used for evaluation of the priming model

A second evaluation of the ORCHIDEE-PRIM model was performed at ecosystem scale against observations of four litter manipulation experiments (Boone et al., 1998; Chemidlin-Prévost-Bouré et al., 2010; Subke et al., 2004; Sulzman et al., 2005) and one compost amendment experiment (Borken et al., 2002). In the litter experiments, two treatments and a control are generally performed. The treatments are total exclusion of above ground litter using nets to prevent fresh litter from falling onto the soil, often transplanting the collected fresh litter to create a second treatment with doubled aboveground litter inputs (Boone et al., 1998; Chemidlin-Prévost-Bouré et al., 2010; Sulzman et al., 2005). For the compost amendment experiment by Borken et al. (2002), 1.4 kg C m^{-2} (and a zero-addition control) of compost was added to the soil. These studies are presented in table 3. When information about soil clay content was not available in the original study, we extracted it from Zobler (1986). The data measured at field scale are the soil CO$_2$ efflux including the heterotrophic respiration but also root respiration in the same flux without clear separation of the two components.

2.3 Optimization procedure

For PRIM, the 6 parameters optimized are turnover rate (k_{SOC}) and priming parameters *c* for each of the three pools (table 2). For the ORCHIDEE soil module, only the three k_{SOC} values are optimized. The same parameters are optimized against the priming incubations dataset described in 2.2.1. Since optimizations were performed using soil incubations data obtained at optimal temperature and soil moisture, we did not optimize the parameters related to the eq. (6) and (7) because the range of observations was quite limited. Optimization was performed in the framework of the Bayesian inversion method with priors (Tarantola, 1987) as described by Santaren et al., (2007) using assimilating all data streams in the same cost function. Assuming that all uncertainties follow Gaussian distributions (parameter error, measurement error, model error), the optimized parameters correspond to a set minimizing the following quadratic cost function:

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$$(9)\quad J(\mathbf{x}) = \frac{1}{2}\left[\left(\mathbf{y}-\mathbf{H}(\mathbf{x})\right)^t \mathbf{R}^{-1}\left(\mathbf{y}-\mathbf{H}(\mathbf{x})\right) + \left(\mathbf{x}-\mathbf{x_b}\right)^t \mathbf{P}_b^{-1}\left(\mathbf{x}-\mathbf{x_b}\right)\right]$$

The cost function defined by equation (9) contains both the mismatch between model outputs and observed data, and the mismatch between optimized parameters and the prior values. The mismatch is weighted by errors of each quantity. $\mathbf{x}$ is the of unknown parameters vector, $\mathbf{x_b}$ the prior values, $\mathbf{y}$ the observations vector and $\mathbf{H(x)}$ the model outputs. $\mathbf{P}_b$ is the prior parameter error variances/covariances, and **R** contains the observational error variances/covariances which represents both measurement uncertainty and model uncertainty.

To minimize the cost function, we used a gradient-based iterative algorithm, called L-BFGS-B (Zhu et al., 1995). A range of values for all the parameters is prescribed by called L-BFGS-B. At each iteration, the cost function J(x) gradient is calculated, with respect to the six parameters. When J(x) is minimized, using a classic finite difference method, we further calculated the posterior error covariance matrix on the parameters P_a from the prior error covariance matrices and the Jacobian of the model at the minimum of the cost function, using the linearity assumption (Tarantola, 1987). When error correlations are close to 1 it suggests that the observations do not permit to clearly separate the effect of two parameters.

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The model H(x) is non linear and therefore the approach to minimize the cost function is sensitive to potential local minima. We get around by performing 30 optimizations with different sets of prior parameter randomly distributed within their variation range. We then used the case providing the lowest cost function. This approach reduces drastically the sensitivity to potential local minima as illustrated in Santaren et al. (2014).

We defined the prior ranges of decomposition rates using literature data (Parton et al., 1988; Gignoux et al., 2001). However, only two studies already estimated the *c* parameter before (Guenet et al, 2013a, Guenet et al., 2013b), its prior value is therefore considered as non-informative and we set a large error on the prior (50%). As for the variance of the model-data mismatch term in the cost function of equation (9), note that with our formalism this error should include both the model error (for instance the model capability to represent the measurement) and the measurement error. Given that the error on the measurements was difficult to estimate precisely for each study, we fixed it to 5% of the mean observed CO_2 flux assuming that all incubation data were independent. At its minimum, J(x) should be close to

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half the number of observations (reduced χ^2 of one). We assumed that all errors (the observations and on the a priori parameters) are uncorrelated.

2.4 Simulations protocol

2.4.1 Simulation protocol for the soil priming model PRIM

Simulations were performed for each incubation experiment presented in 2.2.1 (table 1) as well as for the evaluation sites in 2.2.2. The simulations of the stand-alone PRIM carbon model (i.e. unplugged from the ORCHIDEE full ecosystem model) were run at a daily time step using FOC inputs from table 1 or from the Moyano et al., (2012) database. No spin-up was performed. We started the simulation by prescribing to the soil carbon models with and without priming an initial amount of SOC equal to that measured in the study considered, distributed among active, slow and passive pools as explained in section 2.2.1 At each time step we increment the cumulative heterotrophic respiration coming from SOC mineralization, so that this cumulative simulated CO_2 flux can be compared to data from the end of the incubation experiment. Simulations were performed using R 3.0.2.

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2.4.2 Simulation protocol for ORCHIDEE-PRIM and ORCHIDEE

We ran ORCHIDEE and ORCHIDEE-PRIM at each litter manipulation site presented in table 3 using. 6 hourly climate data obtained from the combination of two existing datasets: the Climate Research Unit (CRU) (Mitchell et al. 2004) and the National Centers for Environmental Prediction (NCEP) (Kalnay et al., 1996). Both models were run using the first ten years of the climate forcing (1901-1909) repeated in a loop, and an atmospheric CO_2 value corresponding to the year 1901. When the simulated relative yearly change of the SOC stock was less than 0.01%, we considered that SOC equilibrium was reached. Once pre-industrial equilibrium was reached in each grid point, we run transient simulations from 1901 until the beginning of the manipulation experiment assuming no land use change driven by reconstructed climate and observed CO_2. Then when the simulation reached the year at which the litter manipulation experiment began, we modified the input of above-ground litter in the same proportion than in the actual manipulation experiments, Finally, we ran the model for each treatment during a period corresponding to duration of each experiment.

2.5 Model evaluation

The model evaluation was performed in two steps. First, we evaluated separately PRIM and the standard first order decay model with their optimized parameters, as stand alone decomposition models, i.e. unplugged from the ORCHIDEE ecosystem model. To evaluate the stand-alone soil models, we used incubation data coming from Moyano et al., (2012) as described in 2.2.2. Secondly, we evaluated ORCHIDEE and ORCHIDEE-PRIM, against litter manipulation experiments (see 2.2.3).

To compare model outputs with data we used different metrics. First a linear mixed effect model with intercept value forced to zero using model outputs as the variable to explain, and data as the fixed effect and the study where data came from as random effect. This approach aimed to take into account the fact that incubations performed within the same study are not independent because they were performed and analyzed by the same team. The linear-mixed effect model gives the slope of the relationship as output. A slope close to one indicates that the model reproduces the data well. Then, we used the Normalized Standard Deviation (*NSD*) or ratio of model to observed standard deviations ; *NSD* = 1 means that the model perfectly reproduces the observed standard deviations across experiments:

$$NSD = \frac{\sqrt{\frac{1}{n} \times \sum_{i=1}^{n} (x_i - \bar{x})^2}}{\sqrt{\frac{1}{n} \times \sum_{i=1}^{n} (o_i - \bar{o})^2}} \qquad (10)$$

where *x* refers to the model value, *o* to the observed value and *n* the number of samples. Finally, we compared model performance using the Bayesian Information Criterion (*BIC*) to take into account that the PRIM soil model has three more priming parameters (one per pool) than the standard model:

$$BIC = \log(MSD) \times n + \log(n) \times p \tag{11}$$

with *MSD* being the mean squared deviation derived from equation (12), *n* the number of data used to evaluate the model, and *p* the number of parameters of the soil model.

$$MSD = \frac{\sum (m-o)^2}{n} \tag{12}$$

with *o* the observed values, *m* the values calculated by the model and *n* the number of observations. The lowest is the BIC the better the model is.

3. Results

3.1 Optimized parameters of the priming model

The parameters obtained after optimization using incubation data described in section 2.2.1 are given in Table 2. The turnover times ranged from a few months (0.30 ± 0.15 year) for the active pool to 462.0 ± 233.8 years for the passive pool, the slow pool being intermediate with 1.12 ± 0.01 years. The priming parameters indicated a decreasing sensitivity with increasing turnover time. The parameter *c* values were 493.7 ± 246.8, 194.0± 97.0 and 136.5 ± 68.3 for the active, slow and passive pools, respectively. Errors correspond to the estimates from the linear assumption at the minimum of J(x). For both, the correlation between parameters was low (data not shown).

After optimization, both models with and without priming parameterization were able to reproduce the cumulative mineralization measured in the different incubations where FOC was added well (Fig. 2, top panel). The slope of the linear regression between optimized model output and incubation measurements was 1.13 for PRIM and 0.93 for the ORCHIDEE soil module. The NSD value (1.80 and 1.52 for PRIM and the standard soil module, respectively) showed that the models overestimated the variance after optimization. When both models were evaluated against the same incubation experiments but without FOM addition, the PRIM model slightly over-estimated accumulated mineralization (Fig. 2 middle panel), as indicated by the value of the slope (1.05). Nevertheless, it performed better than the standard soil module, which underestimated the soil mineralization as indicated by the value of the slope (0.72). The PRIM soil model reproduced quite well the observed priming effect (section 2.2.1) as shown in Fig. 2 (lower panel) with a slope value (1.07). PRIM largely overestimated however the variance of data as indicated by the NSD value (3.14). As expected, the standard soil module was totally unable to reproduce priming (Fig. 2, lower panel).

3.2 Standard soil module vs. PRIM against incubations data

To evaluate the performance of PRIM we tested it against data from soil incubation experiments independent from those used for optimization (see section 2.2.2). We did the same with the standard soil module (Fig. 3). The standard soil module tended to overestimate accumulated mineralization as indicated by a slope value of 1.32 and to underestimate the cross-experiments variance by more than 50% (NSD=0.44). PRIM performed slightly better, but underestimated accumulated mineralization (slope 0.80). The optimized PRIM underestimated the variance by 29%, but the NSD value (0.71) was closer to 1 compared to the standard model. Using the BIC index, which takes into account the higher number of parameters of PRIM, this model still performed better (BIC values of 546.2 vs. 347.4 for standard and PRIM, respectively).

3.3 ORCHIDEE vs. ORCHIDEE-PRIM comparison using *in situ* datasets

When tested at ecosystem-level against litter manipulation experiments, 4 studies x 3 treatments and 1 study with 2 treatments. Both ORCHIDEE and ORCHIDEE-PRIM performed generally well to reproduce the soil CO_2 efflux (Fig. 4). Generally, both versions showed similar performance as indicated by the values of slopes and NSD presented in table 4. The mean slopes are 0.98 for ORCHIDEE-PRIM against 0.97 for ORCHIDEE, and the mean NSD are 1.26 and 1.27, respectively. It must be noted that slope values were generally lower for the treatments excluding litter compared to control and double litter inputs (Table 4). No particular differences of the NSD values were observed between the different litter input regimes. Nevertheless, the BIC index was always higher for ORCHIDEE-PRIM because three more parameters were used by this version compared to ORCHIDEE.

ORCHIDEE-PRIM was able to reproduce the priming observed defined as the difference of CO_2 efflux coming from SOC only with or without litter (Fig. 5), but tended to underestimate its intensity as indicated by the slope value lower than one (0.55). The variance between experiments calculated for priming was overestimated as shown by the NSD value of 1.29. It must be noted that priming was not calculated for ORCHIDEE since the structure of its soil decomposition model does not include a priming mechanisms.

4. Discussion

4.1 PRIM in the context of other soil priming conceptual models

Priming is a complex phenomenon controlled by several mechanisms, such as N mining by microbial communities with different growth strategies, competition between microbial groups for substrate, energy limitations, etc. (Kuzyakov et al., 200; Fontaine et al., 2003; Guenet et al., 2010b). Priming may have important consequences on the feedbacks between climate and C cycle (Schmidt et al., 2011) and it is therefore crucial to better quantify the C fluxes due to priming, especially at large scale (i.e, continental to global). Several models have been developed to describe soil C mineralization with a representation of priming (Gignoux et al., 2001; Fontaine and Barot, 2005; Neill and Gignoux, 2006; Moorhead and Sinsabaugh, 2006; Wutzler and Reichstein, 2008; Neill and Guenet, 2010; Blagodatsky et al., 2010) and such models generally succeeded at reproducing short-term data, mainly incubation. However, to our knowledge, they have never been tested in a range of contrasted situations (different soil types, different FOC amount and chemical composition, different temperature and soil moisture, etc.). Here, we used most of the available incubation data respecting the criteria described in the material and method section. Moreover, previous priming models all needed a high number of parameters compared to PRIM. For these two reasons, the conceptual soil models accounting for soil priming were thus far not included in global land biosphere models (Wutzler and Reichstein, 2008) and very few studies of soil priming at global scale have been performed (Foereid et al., 2014). Here, using a simple scheme with only three additional parameters than the standard soil module of ORCHIDEE, we were able to reproduce priming but also soil mineralization data coming from very different incubation studies performed with different soils at different temperature and moisture, with different time length, etc. The PRIM soil model, which is a microbial steady-state model, might not be able to reproduce short-term response to abrupt change of FOC inputs but with negligible bias over the long term (Wutzler and Reichstein 2013). However, it might have similar performances than more complex models to reproduce long-term trends of FOC inputs (Wutzler and Reichstein 2013). PRIM performed better than the standard soil module to reproduce soil incubation data used to optimize, but it must be noted that the BIC values indicate that the improvement observed with PRIM may be simply due to a higher number of parameters. Nevertheless, when using independent soil incubations data from the one used to optimize the model the improvement is quite clear with BIC values much lower with PRIM than with the standard soil module (347.4 and 546.2, respectively). Furthermore, PRIM was not able to fully catch the observed variability of priming. As discussed above, priming is a complex phenomenon resulting from the interactions of different mechanisms that we summarized in a very simple equation. Therefore, PRIM is probably good in representing a general trends but not all the complexity of the phenomenon. Nevertheless, the

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use of the PRIM soil model seems justified since it increases only slightly the number of parameter of a global land biosphere model and since the parameter values were obtained after optimization on data coming from incubations performed in a range of soils and conditions (different soil types, different ecosystems, different temperatures, different moistures, different amount and type of FOC amended, etc.).

4.2 ORCHIDEE vs. ORCHIDEE-PRIM

4.2.1 Cross sites evaluation

ORCHIDEE-PRIM exhibited similar performance than ORCHIDEE when simulating litter manipulation experiments. It must be noted that both versions share the same scheme for primary production (controlling soil C input by litter), soil temperature and moisture function. The similar performance obtained by the two versions may be due to a model bias for these quantities as well as poorly constrained site histories and climate forcing errors. Since primary production is the main driver of the C input into the soil, the soil CO_2 efflux calculated by the models was largely driven by the capacity of the model to reproduce the observed primary production. In particular, both models largely underestimated the soil CO_2 efflux when litter was removed (Table 4), but obtained good results when litter was kept or when litter was added. This suggests that both models performed quite well when reproducing soil CO_2 efflux, but this was due to bias compensation, meaning that the fraction of CO_2 coming from soil mineralization and root respiration was underestimated and the fraction of CO_2 coming from litter mineralization was overestimated. Moreover, the modification of the litter cover may change the soil humidity and temperature and these effects were not represented in the models.

Finally, the use of microbial steady state model like ORCHIDEE-PRIM present several advantages compared to explicit microbial models. Wieder et al., (2015) identified several challenges related to the incorporation of explicit microbial models in ESMs. In particular, it may induce unrealistic temporal oscillations in response to small perturbations and it needs much more parameter than the classical approach. With ORCHIDEE-PRIM these two difficulties are resolved since we only add three more parameters and because the model is not subject to short-term oscillations.

5. Conclusion

Regarding the several processes that may lead to priming, the satisfactory performance of ORCHIDEE-PRIM compared to observations from both laboratory incubation and field litter manipulation experiments suggests that the simple PRIM conceptual model simulates well the magnitude of observed priming. Consequently, ORCHIDEE-PRIM has the potential to quantify the impact of priming on the soil C cycle at large scales. Nevertheless, ORCHIDEE-PRIM underestimates the priming intensity as shown by the slope value (0.55), indicating that the model still misses important mechanisms explaining the observations. In particular, N availability is an important driver of priming, inducing higher priming when N availability is reduced (Fontaine et al., 2004; Blagodatskaya et al., 2007). The role of N in the priming intensity as well as the extra N mineralization induced by priming and its effect on primary production may represent the next addition to the soil representation in a land surface model by adding a control on the *c* parameter depending on the mineral N availability and on the C:N ratio of the considered pool. Nevertheless, some detailed information on the N dynamic in priming effect experiments would be necessary to do so and very few authors reported the impact of priming effect on N dynamic after FOC additions.

Code availability

For ORCHIDEE, the main part of the code was written by Krinner et al., (2005). The version used here is the 1.9.5.2 version. In this version, compared to the one presented in

Krinner et al., (2005), the albedo representation was improved (Hourdin et al., pers. com.), a routing scheme controlling the flux of water from land surface to the ocean was added (Ngo-Duc et al., 2007) and the dynamic of vegetation was modified (Viovy et al., pers. com.). Furthermore, since 2005 the code has been parallelized. A detailed documentation and the code can be provided upon request to the corresponding author.

ORCHIDEE-PRIM is derived from ORCHIDEE with the modifications presented in the section 2.1.2. A detailed description can be found in Guenet et al., (2013). The code is available upon request to the corresponding author.

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Figure legends

Figure 1: Summarizing scheme of the methods

Figure 2: Scatter plot between data and the PRIM model outputs for the incubations with FOC amendment (a), without FOC amendment (b) and for priming effect (c). The dataset used here are the similar to those used for optimization (a) or are the control incubations (b) and are described in section (2.2.1). Red lines indicate the 1:1 line. Different symbol indicate different studies.

Figure 3: Scatter plot between independent data from optimization (dataset describes in section 2.2.2) and the soil module of ORCHIDEE outputs (a) or between data and the PRIM model outputs (b). Red lines indicate the 1:1 line.

Figure 4: Soil CO_2 efflux calculated by ORCHIDEE on the left side and by ORCHIDEE-PRIM on the right side for the data coming from Boone et al., (1998) (a), from Borken et al., (2002) (b), from Chemidlin-Prévost-Bourré et al., (2010) (c), from Subke et al., (2004) (d) and from Sulzman et al., (2005) (e). Red lines indicate the 1:1 line, black, dashed and dotted lines correspond to control, litter exclusion and litter amendment situations respectively.

Figure 5: Scatter plot between the priming effect measured and the priming effect calculated by ORCHIDEE-PRIM. Red line indicate the 1:1 line and different symbol indicate different studies.

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