We thank the reviewer for providing these comments and provide responses below. Reviewer comments are in bold followed by our responses.

Major comment 1: My first big concern is about correspondence between your solution of eq. (2) (using eqs. (3) and (6-7)) and boundary conditions. […] So suggested general solution does not satisfy both of used boundary conditions. eqs. (3) and (6-7)) and boundary conditions. […] So suggested general solution does not satisfy both of used boundary conditions.

We apologize for an error in the sign of the denominator in Eq. (7) that resulted in this comment. The correct expression for the integration constant B is:

$$B = \frac{C_{CH4} * exp\left(-\sqrt{\frac{k_d}{D_{CH4}}}L\right)}{\left[exp\left(-\sqrt{\frac{k_d}{D_{CH4}}}L\right) - exp\left(\sqrt{\frac{k_d}{D_{CH4}}}L\right)\right]} \quad (7)$$

Inserting A and B into Eq. (3) and solving Eq. (3) for z = 0 and z = L now yields the correct boundary conditions CH_4 (0) = C_{CH4} and CH_4 (L)=0. Equation 7 has been corrected in the revised manuscript. We thank the reviewer for bringing this error to our attention.

The incorrect equation also was present in the code, which produced L values that were too large. However, because the majority of CH_4 is consumed at shallow depth in soil, the overestimation of L resulted in a <1% error in estimates of regional uptake of atmospheric CH_4. We have corrected the MeMo code and rerun the simulations. The changes have not significantly altered the modelling outcomes or conclusions of our study and all numbers have been updated throughout the manuscript.

We note also that use of the term "99.9% consumption" has been changed to 'complete consumption' throughout the manuscript.

2. My second big concern is rationality of building this model in its current state. I suppose that each new model should provide substantial improvement of available models. But in your paper only one class of available models is described and improved (models of Curry, Ridgwell, Potter; further CRP models). To my knowledge there are much better models of methane consumption (as example, Saggar et al., 2007; Zhuang et al., 2013). The main their advantage is description of methane consumption and soil methane diffusion not as constant along the soil profile (like in your model and CRP models) but as dependent on soil depth. These models also take into account all environmental controls considered in your paper. So it is not correct to ignore them.
Ridgwell, Potter; further CRP models). To my knowledge there are much better models of methane consumption (as example, Saggar et al., 2007; Zhuang et al., 2013). The main their advantage is description of methane consumption and soil methane diffusion not as constant along the soil profile (like in your model and CRP models) but as dependent on soil depth. These models also take into account all environmental controls considered in your paper. So it is not correct to ignore them.
That's why it is necessary:

- **to tell that these models exist and to give their brief description**
- **to explain why it is important to build a new model and why your model is better than others. This explanation is necessary to give comparing your model with CRP**

models too. You consider the same factors as CRP models, so what are the reasons to improve these models? Are CRV models or models from (Saggar et al., 2007; Zhuang et al., 2013) predict measured methane fluxes worse than your model or not good enough?

We developed MeMo to be a process-based global model for simulating past, present and future uptake of atmospheric CH_4 by soil. We chose to build on the Potter et al. (1996), Ridgwell et al. (1999) and Curry (2007) (PRC) models because mechanistic simulation of global CH_4 consumption in soil could be forced using data from past archives, modern records and future simulations of climate. We acknowledge that higher resolution models and more complex approaches presently exist for modelling soil methanotrophy, in particular, at a local scale; however, comprehensive global datasets that contain driving data at an adequate spatial and temporal resolution are not available (specific examples are discussed below and in text that has been added to the manuscript).

We have not provided detailed descriptions of non-PRC class models in the manuscript because MeMo builds on the PRC models and demonstrating the advances offered by MeMo was the focus our manuscript. The reviewer notes the Zhang *et al.* (2013) global model (hereafter referred to as 'Z13') for simulating soil uptake of atmospheric CH_4, which can be regarded as separate from the PRC class of models. The general analytical solution used in Z13 is the same as Curry (2007; C07), which has been improved in MeMo; however, Z13 incorporates differences in its parameterization of microbial activity that are based upon redox potential and maximum rates of CH_4 consumption instead of using a base rate for CH_4 oxidation. The Z13 model also differs in that it employs modelled ecosystem-specific inputs for Q10 and optimum soil moisture; however, that complexity requires that Z13 operate within the Terrestrial Ecosystem Model (TEM) because global data sets for parameters such as optimum soil moisture and redox potential are not available. In short, driving data for the PRC and MeMo models are only a portion of the input needed for Z13 simulations and consequently, it was not possible to conduct the same level of comparison between MeMo and Z13 that was conducted for the PRC models. However, we note that the Z13 model was not ignored in our original manuscript and that a comparison of global soil uptake of atmospheric CH_4 simulated by Z13 and MeMo (and a range of other models) was provided in Table 7. The similarity of the global uptake results is a notable outcome despite differences in the modelling approaches used to simulate CH_4 uptake by soil. It is important to note, however, that our study is the first time that a soil methanotrophy model has been validated against global observations, highlighting the importance of accurately quantifying regional variations.

As stated by the reviewer there are biochemical models available at present that are more complex than MeMo (and Z13). These models (e.g., NZ-DNDC and XHAM) have been used to simulate CH_4 dynamics at specific sites based upon coupled reaction transport equations that require highly depth-resolved local input data (e.g., Saggar *et al.*, 2007; Oh *et al.*, 2006; Sabrekov *et al.*, 2016). All of these models can be driven by depth-variable parameters when high resolution local data are available; however, the models are impractical for global simulations of soil methanotrophy because of the limited availability of the high resolution global data required to drive the models (e.g. rhizosphere depth, specific soil management, specific metabolic data, enzyme concentrations).

In summary, attributes of MeMo that advance the state of global simulation of soil uptake of atmospheric CH_4 are (i) its use of an analytical (more complete) solution to quantify the depth and maximum consumption of atmospheric CH_4, (ii) its ability to quantify the influence of

internal CH_4 sources (e.g., methane produced in anoxic microsites in soil) on soil methanotrophy and the impact of autochthonous CH_4 on regional uptake of atmospheric CH_4 by soil linked to seasonal or inter-annual changes in soil moisture or temperature, and (iii) its standalone nature, similar to the PRC models which it is built upon, that eliminates the need to operate within more complex models that provide driving data, and (iv) a detailed validation of simulations both globally and regionally against currently available CH_4 uptake rates for soil methanotrophy.

We did not originally describe all available models in the manuscript because MeMo builds explicitly on the PRC class of soil methanotrophy models. However, we concur with the reviewer that the manuscript would be improved by noting how MeMo differs from these other types of models, in particular Z13. We recognize that addition of the new text is contrary to the second reviewer's recommendation that the manuscript be shortened. The following text has been added on page 3 beginning at line 20 (replacing text formerly from line 20 page 3 to line 19 page 4) to address the concerns raised by reviewer 1:

"Several detailed biogeochemical models have been developed to quantify consumption of atmospheric CH_4 by soil. Saggar et al. (2007) produced a modified version (NZ-DNDC) of DNDC (Li et al., 2000) to evaluate local impacts of changes in climate, soil properties, fertiliser management and grazing regimes on soil methanotrophy. Sabrekov et al. (2016) developed a process-based model of soil CH_4 uptake that also incorporates rhizosphere methanotrophy. Oh et al. (2016) developed a model (XHAM) that explicitly simulates high affinity methanotrophy and active microbial biomass dynamics. These models are driven by high resolution local data sets, which presents challenges for conducting global simulations of soil methanotrophy because of limited availability of input data necessary to drive the models (e.g., global rhizosphere depth, specific soil management, specific metabolic data, enzyme concentrations).

Previous global models included Potter et al. (1996) (hereafter referred to as model 'P96'), which estimates terrestrial uptake of CH_4 by calculating diffusive flux of atmospheric CH_4 into soil using a modified version of Fick´s first law. Ridgwell et al. (1999) (hereafter referred to as model 'R99') improved the P96 model by explicitly accounting for microbial CH_4 oxidation in soil. The R99 model quantifies CH_4 oxidation rates as a function of soil temperature, moisture and N content. The latter parameter was estimated using agricultural land area as a proxy for fertilizer application. Solution of the resulting one-dimensional diffusion-reaction equation was approximated semi-numerically assuming steady state conditions. Curry (2007) (hereafter referred to as model 'C07') employed a steady state analytical solution of the one-dimensional diffusion-reaction equation and introduced a scalar modifier to account for the regulation of CH_4 oxidation rates by soil moisture and the impact of temperature below 0°C. The C07 model continued to use the R99 agricultural land area approximation to evaluate the effect of N loading on CH_4 uptake. The C07 model is employed as a reference model for the Global Carbon Project (Saunois et al., 2016) to estimate global CH_4 uptake in dynamic global vegetation models, such as the Lund-Potsdam-Jena model (LPJ-WHy-Me; Wania et al., 2010; Spahni et al., 2011).

The model of Zhang et al. (2013) (hereafter referred to as model 'Z13') employs the same steady state analytical solution as model C07; however, parameterization of microbial activity in model Z13 is based upon redox potential, ecosystem-specific inputs for Q10 and optimum soil moisture, and maximum rates of CH_4 consumption instead of a base rate for CH_4 oxidation. Consequently, model Z13 operates within the Terrestrial Ecosystem Model (TEM) that provides the necessary driving data because global data sets for many of these parameters are not available. If external data were available, model Z13 presumably could be operated

independently of the TEM in a manner similar to models P96, R99 and C07. However, such a stand-alone application (i.e. decoupled from TEM) would require a new implementation or presumably significant modifications to the code.

We have chosen to focus on refining the R99 and C07 models because availability of new observational and experimental data present an opportunity to re-evaluate global simulations of soil methanotrophy based upon an enhanced version of these models. For example, new global datasets quantifying N deposition and N input via fertilizers now enable better representation of this key inhibitory effect on soil uptake of atmospheric CH_4 (Lamarque et al., 2013). In addition, a new global inventory of CH_4 uptake rates in soil (Duataur and Verchot, 2007) provides a means to better compare and valid model simulations.

3. Using L, the depth of total methane consumption, is good idea, but total methane consumption (or consumption up to 0.1% of atmospheric methane level) does not occur in natural upland soils. There is a certain threshold of methane consumption by microorganisms. Methane consumption stops if this threshold is reached because microorganisms cannot get enough energy by methane oxidation for cell maintenance (Stackhouse et al, 2017). According to literature methane concentration is never close smaller than 0.1 ppm in deep soil horizons and consumption declines to zero in deep soil layers – about 50-70 cm (Bender and Conrad (1992), Whalen et al (1992), Czepiel et al (1995), Priemé and Christensen (1997), Jensen and Olsen (1998)). To my knowledge biological consumption of methane was not ever investigated on a depth more than 1 m in upland soils. Threshold of consumption varies depend on ecosystem type, climate and is defined by oxidation efficiency of methanotrophs (see references above and Stackhouse et al, 2017).

That's why I think that this approach of using total methane consumption depth is not correct.

We thank the reviewer for this suggestion. It is straightforward to incorporate a CH_4 threshold, CH_4 min, in Eqs. 6 and 7 for the case CH_4 (L) = CH_4 min. In the original manuscript CH_4 min = 0 but it is now a variable that can be set in the model:

$$A = -\frac{C_{CH_4} * exp\left(\sqrt{\frac{k_d}{D_{CH_4}}}L\right) - CH4min}{\left[exp\left(-\sqrt{\frac{k_d}{D_{CH_4}}}L\right) - exp\left(\sqrt{\frac{k_d}{D_{CH_4}}}L\right)\right]} \quad (6)$$

$$B = \frac{-CH4\ min + C_{CH_4} * exp\left(-\sqrt{\frac{k_d}{D_{CH_4}}}L\right)}{\left[exp\left(-\sqrt{\frac{k_d}{D_{CH_4}}}L\right) - exp\left(\sqrt{\frac{k_d}{D_{CH_4}}}L\right)\right]} \quad (7)$$

Eq. (8) becomes:

$$0 = -D_{CH4}\sqrt{\frac{k_d}{D_{CH4}}}\ \frac{\left(2\ C_{CH4} - CH4min * exp\left(-\sqrt{\frac{k_d}{D_{CH_4}}}L\right) - CH4min * exp\left(\sqrt{\frac{k_d}{D_{CH_4}}}L\right)\right)}{\left[exp\left(-\sqrt{\frac{k_d}{D_{CH_4}}}L\right) - exp\left(\sqrt{\frac{k_d}{D_{CH_4}}}L\right)\right]} - F_{CH4} \quad (9)$$

To evaluate the effect of using a CH_4 threshold of 0 or 0.1 ppm, we compared the two scenarios. Figure 1 shows that the difference in L between CH_4 (L) = 0 and CH_4 (L) = 0.1 ppm is ~5 cm, which will have a minimal impact on CH_4 uptake flux because the majority of CH_4 is consumed

in the top 10 to 30 cm of soil. Based on these changes and analysis we made the following modifications to the manuscript:

1) Updated Eqs. (6), (7) and (9) in the text.
2) Added Figure R1 to the Supplementary file (page 1; Figure S1).
3) Replaced Eq. (9) in the MeMo code for calculation of L.

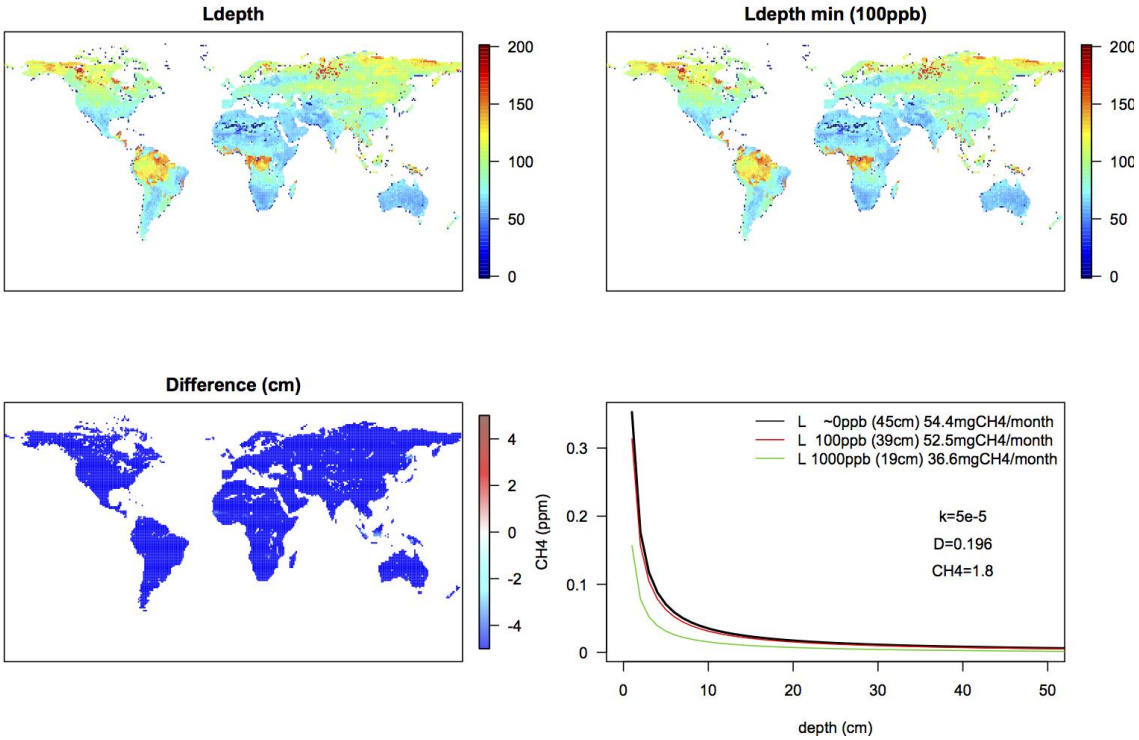

Figure R1 (also Supplementary Fig S1): Comparison of model-derived depth L when CH_4(L) = 0 (top left), CH_4 (L) = 0.1 ppm (top right), the difference in depth L using the two approaches (bottom left), and CH_4 consumption profiles in soil and total uptake flux using fixed parameters of k, D and CH_4 (bottom right).

Under optimal conditions for methanotrophy, a CH_4 min = 0.1 ppm threshold results in a reduction in L of 6 cm (Supplementary Figure R1 bottom right panel); however, conditions for methanotrophy vary spatially and temporally, and hence use of the 0.1 ppm CH_4 threshold globally yields an average L reduction of 5 cm. The impact on CH_4 uptake rates is negligible because ~90% of atmospheric CH_4 entering soil is consumed within 10 cm of the ground surface. The effect on L size is important when CH_4 min is at least > 0.35 ppm, for example when CH_4 min =1.0 ppm the uptake flux decreases by ~57%.

Thus, the inclusion of a 0.1 ppm threshold for soil methanotrophy does not have an impact on the estimation of the global uptake of atmospheric CH_4, when compared with a scenario in which it is assumed that all CH_4 entering soil is consumed.

4. Page 5, rows 15-20. It would be better to give here any estimates, why only diffusive transport and biological consumption should be considered. What about convective transport? Is it always can be omitted? Why term on a right side of eq. (2) is not important? Are conditions really always steady state?

Several studies have shown that soil methanotrophy is limited by CH_4 diffusion and that advective fluxes (convective fluxes do not operate at this scale) play only a minor role in CH_4 under particular circumstances (Striegl, 1993; Kruse et al., 1996). Regardless, advective fluxes can be readily incorporated in the model (see below) although cannot be parameterized or constrained because of a lack of driving data.

To incorporate advective flux in MeMo an additional advective term is added to the diffusion-reaction equation. Assuming the following boundary conditions: (i) C(0) = C0 and (ii) $\frac{dCH_4}{d_z}|_{z->\infty} = 0$ the solution of the advection-reaction-diffusion equation is given by:

$$J_{CH4} = -D_{CH4}(A * a + B * b) - \mathrm{wC}$$

Where w is the advective velocity and C is defined as:

$$\mathrm{C(z)} = \mathrm{A} * \exp\,(a * z) + \mathrm{B} * \exp(b * z)$$

Where:

$$a = \frac{\left(w - \sqrt{w^2 + 4 * D_{CH4} * k_d}\right)}{2 * D_{CH4}}$$

$$b = \frac{\left(w + \sqrt{w^2 + 4 * D_{CH4} * k_d}\right)}{2 * D_{CH4}}$$

Thus, if $w = 0$ the solution is Eq. 10 currently in the manuscript. Solution of the equation using different values of w yields the CH_4 depth profiles shown in Figure R2 below.

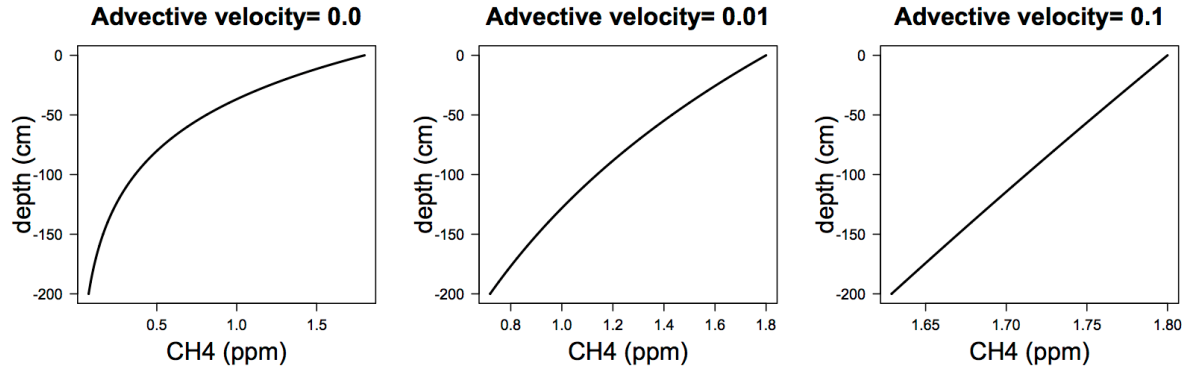

Figure R2: Calculation of CH_4 flux using different values of downward advective velocity (w). The depth (z) in soil at which CH_4 is 0.1 ppm occurs is shown in each panel.

The analysis shows that an advective velocity of 0.01 cm^2/s can reduce the depth (L) of complete CH_4 consumption by up to 20% under optimal conditions. An advective velocity of 0.1 cm^2/s (half the rate of diffusion) can cause a decrease of up to 50%. However, as stated initially no data exist at present to parameterize or valid incorporation of advection into soil methanotrophy models.

4. Page 5, rows 15-20. Are conditions really always steady state?

It is reasonable to assume steady state conditions in global models such as MeMo because the timescale of boundary condition changes is long compared to the time required to attain steady state conditions in soil.

2. Page 10. What is the reason of using old Moldrup paper (same as in Curry paper) while there is much more recent and better soil gas diffusion model in (Moldrup et al., 2013)?

We have cited the Moldrup et al. (2013) paper in our work. While the authors evaluate several soil-diffusion models, it is important to note that their performance was only slightly better than the one employed in MeMo:

$$\frac{Dp}{Do} = \Phi^{4/3}\left(\frac{\Phi_{air}}{\Phi}\right)^{1.5+3/b}$$

The new version proposed by Moldrup et al. (2013) is:

$$\frac{Dp}{Do} = {\Phi_{air}}^{2}\left(\frac{\Phi_{air}}{\Phi}\right)$$

Where *Dp* is the gas diffusion coefficient in soil (cm^3 air cm^{-1} soil s^{-1}), *Do* is the gas diffusion coefficient in free air (cm^2 air s^{-1}), Φ is total pore volume (cm^3 cm^{-3}), Φ_{air} is air-filled porosity (cm^3 cm^{-3}), *b* is a scalar that accounts for soil structure ($b = 15.9\ f_{clay} + 2.91$).

The new version of the gas diffusion equation from Moldrup et al. (2013) provides only a marginal improvement in the RSME fit (0.017; Figure 2 in Moldrup et al., 2013) versus the model we used in MeMo (RSME=0.028). However, the main reason that we use this formulation of the equation is that the new model no longer includes the soil structure parameter (b) that accounts for the effects of clay content on gas diffusion in soil. Data for this parameter are available globally for different soil types which enables a more explicit assessment of the impact of soil texture on global uptake of atmospheric CH_4.

3. Page 30, row 11. Please fix, Sabrekov (like in list of references), not Savrekov.

This error has been corrected.

References

Moldrup, P., Iversen, N.: Modeling Diffusion and reaction in soils: II Atmospheric Methane Diffusion and consumption in a forest soil, Soil Sci. 161, 355-365, 1996.

Kruse, C.W., Moldrup, P., Iversen, N.: Modeling Diffusion and reaction in soils: II Atmospheric Methane Diffusion and consumption in a forest soil, Soil Sci. 161, 355-365, 1996.Stange, F., Butterbach-Bahl, K., Papen, H.: A process-oriented model of N2O and NO emissions from forest soils: 1. Model development, J. Geophys. Res. Atmospheres 105, 4369–4384, doi:10.1029/1999JD900949, 2000.

Li, C., Aber, J., Stange, F., Butterbach-Bahl, K., Papen, H.: A process-oriented model of N2O and NO emissions from forest soils: 1. Model development, J. Geophys. Res. Atmospheres 105, 4369–4384, doi:10.1029/1999JD900949, 2000.Trugman, A.T., Moch, J., Onstott, T.C., Jørgensen, C.J., D'Imperio, L., Elberling, B., Emmerton, C.A., St. Louis, V.L.,

Medvigy, D.: A scalable model for methane consumption in arctic mineral soils, Geophys. Res. Lett. 43, 2016GL069049, doi:10.1002/2016GL069049, 2016.

Oh, Y., Stackhouse, B., Lau, M.C.Y., Xu, X., Trugman, A.T., Moch, J., Onstott, T.C., Jørgensen, C.J., D'Imperio, L., Elberling, B., Emmerton, C.A., St. Louis, V.L., Medvigy, D.: A scalable model for methane consumption in arctic mineral soils, Geophys. Res. Lett. 43, 2016GL069049, doi:10.1002/2016GL069049, 2016., A.F., Glagolev, M.V., Alekseychik, P.K., Smolentsev, B.A., Terentieva, I.E., Krivenok, L.A., Maksyutov, S.S.: A process-based model of methane consumption by upland soils. Environ, Res. Lett., 11, 075001, doi:10.1088/1748-9326/11/7/075001, 2016.

Sabrekov, A.F., Glagolev, M.V., Alekseychik, P.K., Smolentsev, B.A., Terentieva, I.E., Krivenok, L.A., Maksyutov, S.S.: A process-based model of methane consumption by upland soils. Environ, Res. Lett., 11, 075001, doi:10.1088/1748-9326/11/7/075001, 2016.Giltrap, D.L., Lambie, S.M.: Measured and modelled estimates of nitrous oxide emission and methane consumption from a sheep-grazed pasture, Agric. Ecosyst. Environ, 122, 357–365, doi:10.1016/j.agee.2007.02.006, 2007.

Saggar, S., Hedley, C.B., Giltrap, D.L., Lambie, S.M.: Measured and modelled estimates of nitrous oxide emission and methane consumption from a sheep-grazed pasture, Agric. Ecosyst. Environ, 122, 357–365, doi:10.1016/j.agee.2007.02.006, 2007.Wania, R., Neef, L., van Weele, M., Pison, I., Bousquet, P., Frankenberg, C., Foster, P.N., Joos, F., Prentice, I.C., van Velthoven, P.: Constraining global methane emissions and uptake by ecosystems, Biogeosciences 8, 1643–1665, doi:10.5194/bg-8-1643-2011, 2011.

Spahni, R., Wania, R., Neef, L., van Weele, M., Pison, I., Bousquet, P., Frankenberg, C., Foster, P.N., Joos, F., Prentice, I.C., van Velthoven, P.: Constraining global methane emissions and uptake by ecosystems, Biogeosciences 8, 1643–1665, doi:10.5194/bg-8-1643-2011, 2011., R., Ross, I., Prentice, I.C.: Implementation and evaluation of a new methane model within a dynamic global vegetation model: LPJ-WHyMe v1.3.1., Geosci Model Dev 3, 565–584, doi:10.5194/gmd-3-565-2010, 2010.

Wania, R., Ross, I., Prentice, I.C.: Implementation and evaluation of a new methane model within a dynamic global vegetation model: LPJ-WHyMe v1.3.1., Geosci Model Dev 3, 565–584, doi:10.5194/gmd-3-565-2010, 2010.Saikawa, E., Lu, Y., Melillo, J.M., Prinn, R.G., McGuire, A.D.: Response of global soil consumption of atmospheric methane to changes in atmospheric climate and nitrogen deposition, Glob. Biogeochem. Cycles 27, 650–663, doi:10.1002/gbc.20057, 2013.

Zhuang, Q., Chen, M., Xu, K., Tang, J., Saikawa, E., Lu, Y., Melillo, J.M., Prinn, R.G., McGuire, A.D.: Response of global soil consumption of atmospheric methane to changes in atmospheric climate and nitrogen deposition, Glob. Biogeochem. Cycles 27, 650–663, doi:10.1002/gbc.20057, 2013.