

List of changes in the manuscript marked with bold typeface.

| Reviewer 1 Reviewer's comment | Author's comment - page and line numbers refer to the reviewed version |
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| | Thank you for the review. |
| Good summary of the paper but a bit more information about the methods should be given in the abstract if possible. | We will add a sentence after line 8: "In principle, controlling factors were discretized into classes, each class associated with a probability and linked to an output variable. This creates a network of links that are ultimately linked to a set of equations for carbon input and output to and from soil C pools." |
| 'The first scenario, "limited NPP", represents a change in productivity caused by temperature and precipitation alone, which could be similar to the net effect of CO ₂ fertilization and nutrient-constrained growth' needs more justification. | This seems to be a misunderstanding. The model behind the 'limited NPP scenario' does not include any CO ₂ effect, so any increase of NPP is only due to an increase in temperature or precipitation. This absence of a CO ₂ -fertilization could be similar to a limitation by nutrients. |
| The limitation of the CO ₂ fertilisation affects by nutrient availability is mentioned in the introduction, but limitation due to elevated CO ₂ and temperature interactions should also be mentioned in the second paragraph of the introduction. | There may be a misunderstanding. Limitation due to elevated CO ₂ and temperature interaction is addressed in the text beginning page 365-line 8 ("The large variation ..."). |
| Pg 366 line 4 give some examples of some of the impacts. | These are events like fire, and erosion, but also insect outbreaks, erosion, landslides, windthrow and flooding. |
| Pg 366 give the year you are referring to when you say 'present day' to make things easier for the reader in the future. | We take 2010 as the base year for calculations. Clarification inserted in the text, line 25. |
| Somewhere in the methods the uncertainties associated with working at a 5° grid should be acknowledged. | We use a 30 arc minute grid (0.5°), p367-line4. The sub-pixel variation is now addressed in text inserted after p367-line 5 and page 369-line19. |
| What was the rationale behind choosing harvest index as a land use parameter? | This is a typo in page 367-line 4. The 'harvest factor' is the closest relationship between land use and the C cycle in our opinion and, as explained in page 370-line 25, is practical for estimating the effects of future land use on NPP. |
| When was a steady state reached in the organic soils? | We never explicitly calculated when a steady state was reached - we changed the text in page 367-line 23 to prevent a possible misunderstanding. Before we implemented the formula in the model, we applied it in a spreadsheet and, picking |

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| | reasonable values, we observed that a steady-state ($\Delta C < 0.1$ kg/m ² /yr) was reached within 75 years in most cases. |
| Page 368 Ln 27 clarify what is meant by 'not too small' values of fmf. Although the reader is referred to the supplement clarification is needed here. | We can draw the line at fmf=0.1. This information is added to the revised text. |
| Pg 369 mention the possible limitation of the CO ₂ fertilisation effect by elevated temperature. The authors say the limited NPP scenario, 'could be similar to the net effect of CO ₂ fertilization and nutrient-constrained growth' [page 370, line 5] please explain why you think this. | This seems to be a misunderstanding. The model behind the 'limited NPP scenario' does not include any CO ₂ effect, so any increase of NPP is only due to an increase in temperature or precipitation. This absence of a CO ₂ -fertilization could be similar to a limitation by nutrients. We have revised the sentence. |
| Fig. 2 in Paul et al., 2002 should be reproduced in the supplemental material if possible. | The relevant part of the figure is also available in this online document (Paul 2001) http://www.kirschbaum.id.au/NEE_Workshop_Proceedings.pdf Maybe this URL would be a sufficient hint. |
| Page 372 lines 2-4, ["that leaf litter and fine root litter on the one hand and dead wood (above- and belowground) on the other hand contribute on average equal proportions to litter input entering forest soils"] does this assumption hold for non-deciduous forests? | At a global scale and given the heterogeneous methods used in the reports cited in the literature, we believe that our generalisation is backed by observations and also applies, <i>grosso modo</i> , to coniferous forests. |
| Results p375 Ln 21 Greatest sensitivity to fmf is a reasonable finding as fmf covers a wide range of parameters. | (no comment) |
| p376 Ln 7-9 interesting finding. | (no comment) |
| End of section 3.2 on page 376, what were the findings for areas of pristine forest converted to grasslands? This is always a controversial land use change when looking at long term SOC stock changes. | On the "global scale" the assumed probability of transition from tropical pristine forest to pasture was set to a low value (0.01), hence we did not want to draw conclusions from a small sample. In individual pixels the response was more drastic and is referred to on page 380-line 5. The sentence applies not only to cropland but also pastures (see Supplement 5, last lines of Table S5.2) and was corrected. |
| Pg 378 lines 15 - 20, this point highlights the caution that should be exercised when making any local inferences from a global analysis. Land use conversion from native land to cropland may show an increase in | (no comment) |

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| <p>SOC, but, as the authors point out, this is assuming inputs are higher than under native vegetation and the question arises as to where those inputs come from in hot desert environment.</p> | |
| <p>P379, last 3 lines, interesting point. More data is needed on SOC stocks in shrublands.</p> | (no comment) |
| <p>Would have been good to mention in the discussion CO2 fertilisation effects and limitations of this by temperature.</p> | |
| <p>Not surprising that the greatest uncertainty is associated with carbon rich soils, presumably because of lack of understanding of the impacts of key variables on anaerobic decomposition.</p> | (no comment) |
| <p>End of page 382, linking socio- economic models to vegetation models is still in its infancy in many respects and more work needs to be done on understanding the socio-economic drivers of vegetation change at the global level.</p> | We agree. |

List of changes in the manuscript marked with bold typeface.

| <p>Reviewer 2</p> <p>Reviewer's comment</p> | <p>Author's comment - page and line numbers refer to the reviewed version</p> |
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| | <p>Thank you for the review. It appears that page number references are off by 1 page.</p> |
| <p>... I think the paper would be improved if the authors provided more clarity and emphasis on how wetlands and permafrost zones were handled in the analyses. In particular I found it difficult to discern how wetlands (including peatlands) were parameterized and how peatlands in permafrost zones were handled.</p> | <p>We agree that in this particular field the explanations could be improved. Further explanations are provided below.</p> |
| <p>I was unable to open the files in Supplements 1 and 2.</p> | <p>We have clarified the instructions for files 1 and 2 contained in the Supplement. "To be used with Netica (Norsys, Vancouver, Canada). Readable with any text browser (change the file name tag to '.txt')."</p> |
| <p>There is no mention, in the introduction or discussion, of the potential impact of natural disturbances (e.g., wildfire, insect outbreaks, windthrow, etc.) on soil C dynamics. [...]</p> | <p>We have added examples after line 3 p366 as suggested by reviewer 1.</p> |
| <p>Page 367 lines 11-17; Is there a mechanism in your model or algorithms that allows for carbon [in] the inaccessible pool to transfer to one of the accessible pools as a result of climate change, land-use, or land-use change? Please explain.</p> | <p>Within one instance in time, the inaccessible pool does not participate in the decomposition of organic matter. However, the fraction of the total C pool that is inaccessible can differ between reference and target conditions due to e.g. differences in water-logging or melting of permafrost. We added a clarifying sentence after line 17, p 368.</p> |
| <p>Page 369 lines 16-18; indicates all inputs (equal to NPP) go into the fast and slow pool; then on page 367 lines 5-7 all inputs go only into the fast pool. Please clarify. If inputs go to both the fast and slow pools please explain the rationale for how the inputs are split between the fast and slow pools.</p> | <p>We intended to say in lines 16-18 that all NPP initially goes into the fast pool, which is part of the accessible pool. We shortened the sentence ("is added to the fast pool") for clarity.</p> |
| <p>Page 369 lines 24-25; It would help if you could explain the difference between your definition of zonal and azonal. Here you appear to describe wetlands as only being "azonal". There are areas in the world where wetlands (e.g., peatlands) are zonal, as I would define them (widespread, dominant soil type). Please clarify.</p> | <p>We agree that wetlands can be part of the zonal vegetation. While trying to keep the text to the point, we now refer to wetlands as a special vegetation type and land cover and clarify that we mean climatic vegetation zones.</p> |
| <p>Page 371 lines 1 and 2; Please expand your explanation of how oxygen availability is</p> | <p>Oxygen availability is a characteristic derived from the HWSO by Fischer et</p> |

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| <p>determined, what data is used from the HWSD and how?</p> | <p>al. and we used their product. A short explanation is currently available here: http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/ We added from this summary a little more information in the text but otherwise refer the reader to the original publication.</p> |
| <p>Page 371 lines 22-24; I looked at Grace et al. 2006 which appears to apply only to mineral soils. Did you use the same expression based on CEC for organic soils that can have CEC values that are much higher than occur in mineral soils? Please clarify if this expression was only applied to mineral soil which would be appropriate.</p> | <p>In calculating the CEC of the soil we considered only soils with <20% OC content. This is now specified in the revised text.</p> |
| <p>Page 375 lines 6-9; Please explain how C is protected by high CEC. How would this apply to organic soils?</p> | <p>This explanation refers only to mineral soils and 'protected' should be better phrased as "stabilized". This has been specified in the revised text.</p> |
| <p>Page 377 line 27; Would you explain which tundra regions in the world are expected to be able to support boreal forest plantations? Where would soil profiles be thick enough to support plantations?</p> | <p>The conversion of boreal forests is hypothetical. We considered only climatic conditions (i.e. vegetations zones). This is now mentioned in the updated version in the Methods section (end of section 2.4).</p> |
| <p>Page 378 lines 2 and 3; This is an example where it was difficult for me to interpret or understand the statement because wetlands were not treated explicitly enough in the paper. This statement may be true for mineral soil permafrost areas that might convert to wetlands, but we also have permafrost peatlands that are already wetlands. What is expected to happen when they thaw?</p> | <p>The conditions 'wetland' and 'depth of active layer' imply a restriction of the fraction of the soil accessible to decomposition and we use the minimum depth of both. That is, decomposition in a wetland with a deeper active layer after thawing would still be constrained by a high water table associated with wetlands. This is now explained in the Methods section.</p> |
| <p>Page 378 line 4; Again a more explicit treatment of peatlands would help with interpreting this statement. Do you mean that regions that are boreal now, and remain boreal in the future will have more timber plantations and arable land? Or areas that are now Arctic or tundra, become boreal and they will have more timber plantations and arable land? For example, as one moves north in the boreal of Canada peatlands become more dominant on the landscape. It</p> | <p>We generally consider only the climatic but not the edaphic suitability for a change in vegetation. The exact transition probabilities are listed in Table S4.3 in the Supplement. For wetlands, we assume that they remain wetlands in cold climates and have a low probability ($\leq 3\%$) of drying out in warmer climates. This information</p> |

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| <p>is unlikely that even if climate changes that these peatlands are an appropriate soil type for plantations or arable land. Please clarify your thinking.</p> | <p>is now added to the main text. The explicit land-use conversions in point comparisons are also hypothetical and illustrate the potential effects without regard for the appropriateness of soil conditions for such a change.</p> |
| <p>Page 379 lines 17-20; But doesn't Todd-Brown et al. 2014 question the validity of these models in the first paragraph of their conclusions?</p> | <p>Yes, he does. We wanted to point out that our approach (in the unlimited NPP scenario) produces comparable results as mechanistic models do. Our results under the limited-NPP scenario support Todd-Brown's concerns.</p> |
| <p>Page 372 lines 2-3; This statement is just a little bit unclear. Does your statement mean "Above- and belowground fine (leaf and fine roots respectively) and above- and belowground coarse (coarse woody debris and coarse roots respectively) contribute. . . ." Please clarify.</p> | <p>Yes, this is a better way of putting our statement on p. 373. We adopted the phrasing in the manuscript.</p> |
| <p>Page 374 line 21; Is NNP a typo? Should it be NPP? If this is the case NNP also appears in Supplement 3, page 5 and should be corrected.</p> | <p>Yes, a typo. Thank you. Typo corrected in the revised text.</p> |

1 **Global distribution of soil organic carbon — Part 2:**
2 **Certainty of changes related to land use and climate**

3
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Martin Köchy 2014-12-10 12:57

Gelöscht: in soil organic carbon

Martin Köchy 2014-12-10 12:58

**Gelöscht: and land use change at
global and grid-cell scales**

Martin Köchy 2014-12-10 12:59

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1 **Abstract**

2 Global biosphere models vary greatly in their projections of future changes of global soil
3 organic carbon (SOC) stocks and aggregated global SOC masses in response to climate
4 change. We estimated the certainty (likelihood) and quantity of increases and decreases on a
5 half-degree grid. We assessed the effect of changes in controlling factors, including net
6 primary productivity (NPP), litter quality, soil acidity, water-saturation, depth of permafrost,
7 land use, temperature, and aridity, associated by probabilities (Bayesian Network) on an
8 embedded temporally discrete, three-pool decomposition model. In principle, controlling
9 factors were discretized into classes, each class associated with a probability and linked to an
10 output variable. This creates a network of links that are ultimately linked to a set of equations
11 for carbon input and output to and from soil C pools. The probability-weighted results show
12 that, globally, climate effects on NPP had the strongest impact on SOC stocks and the
13 certainty of change after 75 years. Actual land use had the greatest effect locally because the
14 assumed certainty of land use change per unit area was small. The probability-weighted
15 contribution of climate to decomposition was greatest in the humid tropics because of greater
16 absolute effects on decomposition fractions at higher temperatures. In contrast, climate effects
17 on decomposition fractions were small in cold regions. Differences in decomposition rates
18 between contemporary and future climate were greatest in arid subtropical regions because of
19 projected strong increases in precipitation. Warming in boreal and arctic regions increased
20 NPP, balancing or outweighing potential losses from thawing of permafrost. Across
21 contrasting NPP scenarios tropical mountain forests were identified as hotspots of future
22 highly certain C losses. Global soil C mass will increase by 1% with a certainty of 75% if
23 NPP increases due to carbon-dioxide fertilization. At a certainty level of 75%, soil C mass
24 will not change if CO₂-induced increase of NPP is limited by nutrients.

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Martin Köchy 2014-11-6 22:04
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that uses categorized driver variables

1 1 Introduction

2 Soil organic carbon (SOC) represents about three quarters to four fifths of the terrestrial
3 organic carbon (C) mass (Prentice et al., 2001). The mean turnover rate of SOC is slower than
4 that of any other terrestrial organic pool (Reeburgh, 1997). Due to its size, small relative
5 changes in the SOC mass can have large effects on atmospheric CO₂ concentration and hence
6 on climate change.

7 Global SOC mass in five general circulation models (GCM) was projected to change by
8 between -46 Pg and +51 Pg (Schaphoff et al., 2006) by the end of the century. Eleven earth
9 system models even showed a range of projected changes between -72 Pg and +253 Pg for a
10 high-CO₂ scenario (Todd-Brown et al., 2014). Projections also differ in where changes occur
11 (Sitch et al., 2008). The large variation in expected future changes is due to the balance of, on
12 one hand side, different expected increases of carbon input from net primary productivity
13 (NPP) by CO₂ fertilization and higher temperatures and, on the other hand side, faster
14 decomposition accelerated by higher temperatures (Davidson and Janssens, 2006, Smith et al.,
15 2008). The point of balance may vary over the course of time (Jones et al., 2005).
16 Furthermore, although NPP might increase in the future because of increasing concentrations
17 of CO₂ in the atmosphere (CO₂ fertilization), productivity may still be limited by the
18 availability of nitrogen or other resources (Gedalof and Berg, 2010, Norby et al., 2010, Todd-
19 Brown et al., 2014).

20 With this wide range of projected changes in the global mass of SOC one may wonder how
21 likely increases or decreases of SOC stocks (mass of organic carbon per volume of soil) are in
22 response to potential changes in C input and climate across the world? One way to address the
23 certainty of projections is to obtain a frequency distribution of the ensemble output of several
24 models as has been done for changes in climate (e.g., Power et al., 2011). This approach
25 however cannot formally address the uncertainty in the parameters of the models. This rather
26 requires consideration of the frequency distribution of the values of many potentially
27 controlling factors of the organic carbon cycle.

28 The effect of the frequency distribution of parameters on SOC stocks, the global SOC mass,
29 and SOC changes was assessed for one model (Hararuk et al., 2014) using a Markov Chain-
30 Monte Carlo approach for model calibration. The distribution parameters in the model caused
31 SOC losses ranging between 15 and 100 Pg for a scenario implying high greenhouse-gas
32 emissions and mean global temperature increases ('RCP8.5'). This study focused on the

1 approach and a global perspective and left out other import impacts that affect SOC stocks
2 and masses regionally and globally, e.g. [fire](#), [insect outbreaks](#), [erosion](#), [landslides](#), [windthrow](#),
3 [flooding](#).

4 For a richer picture of the change of global SOC mass, wetland soils, including peatlands,
5 which contain at least 6–12% of the global SOC mass in the upper 1 m (depending on the
6 definition and estimated area of wetland, Köchy et al., 2014), and permafrost regions,
7 containing about 40% of the global SOC mass in the upper 1 m (Köchy et al., 2014) must be
8 considered as well. Furthermore, SOC stocks are not only affected by climate change but
9 probably even more so by change in land use (Brovkin et al., 2013). This is especially true for
10 organic soils because they contain >15% of the global SOC mass in the top 1 m (Köchy et al.,
11 2014). SOC losses from organic soils in Scotland, for example, are expected to be c. 3.5 times
12 greater than losses from C-poor soils (Smith et al., 2010). In C-rich wet or water-logged soils,
13 decomposition of organic matter is slow because of lack of oxygen (Armentano and Mengeo,
14 1985, Mitra et al., 2005, Smith et al., 2008). Draining of wetlands exposes C to oxygen.
15 Outside wetlands, conversion of natural forests to grassland or cropland causes drastic losses
16 in temperate (Poeplau et al., 2011) and tropical regions (Holmes et al., 2006, Don et al.,
17 2011). Organic matter in the soil can also be physically protected from microbial
18 decomposition by adsorption to soil particles (Six et al., 2002, Six et al., 2002, Davidson and
19 Janssens, 2006) or permafrost.

20 The relative impacts of climate change, land use change, and thawing of permafrost on SOC
21 stocks of mineral and organic soils have been studied with great detail only at small or
22 regional scales (e.g. Grosse et al., 2011). There is a lack of a comprehensive global
23 assessment of the certainty of soil C changes (Vesterdal and Leifeld, 2007). In the present
24 study we quantify the uncertainty of changes of present-day SOC stocks ([c. 2010](#)) due to
25 projected changes in climate and land use by aggregating the uncertainty or variability in
26 controlling variables, and their effects on SOC stocks. In addition, we identify where soils are
27 most likely to be vulnerable at the global scale and with relevance to the global carbon cycle.

28

29 **2 Methods**

30 We assess the effects of climate (temperature, aridity), soil (acidity, permafrost, aerobicity, C
31 adsorption), vegetation (vegetation type, litter quality), and land use (via NPP, harvest [factor](#),
32 and litter quality) on SOC stocks at a spatial resolution of pixels with 0.5° latitude by 0.5°

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1 | longitude. [We acknowledge that variation in soil, vegetation, environmental, land use and](#)
2 | [other factors controlling SOC decomposition exists within a pixel. This variation is partly](#)
3 | [included in our analysis but we cannot quantify its contribution to overall uncertainty.](#)

4 | For quantifying the certainty of SOC changes over a period of 75 years (2010–2085) we apply
5 | a quasi-steady-state three-pool model of SOC decomposition to historic SOC stocks within an
6 | environmental framework (Fig. 1) and compare differences between future reference and
7 | target conditions. Historic conditions correspond to SOC stocks of c. 1950-2000 of the top 1
8 | m under current (c. 1980-2010) climate and land use. Future conditions are characterized by
9 | projected climate and land use of 2075-2100. Reference conditions imply no change in
10 | environment, whereas target conditions imply changes in climate, vegetation, and land use.
11 | For comparisons of reference and target conditions, we keep local (within pixel) settings of
12 | soil pH, CEC, and constraints of O₂ availability (unless caused by a change of land use to or
13 | from wetland) constant.

14 | SOC stocks in reference and target conditions are prescribed by decomposition under constant
15 | ranges of monthly temperature, monthly precipitation, litter input, and land use for 75 years
16 | starting with the historic SOC stock. (We account for the expected gradual change in climate
17 | and land use in an additional step.) We compare reference with target SOC stocks after 75
18 | years instead of steady-states with $t \rightarrow \infty$ in order to compare the same points of time across all
19 | soil conditions of the world in the spatial analysis and for compatibility with the point of time
20 | of projected NPP and climate values. [Examination of our decomposition formulas in a](#)
21 | [spreadsheet indicated that a steady-state is reached within 75 years in most mineral soils and](#)
22 | non-extreme environments. In other words, by considering a defined, limited time period we
23 | compare two possible outcomes (reference vs. target conditions) for the same year. This
24 | facilitates comparisons with projections of C stocks for the end of the century by other
25 | authors.

26 | In the following sections we describe first the core decomposition model and then how
27 | environmental factors affect the values of the decomposition parameters.

28 | 2.1 Characterization of the Harmonized World Soil Database

29 | We consider three pools of SOC —fast (C_{fast}), slow (C_{slow}), and inaccessible— that differ in
30 | their maximum annual decomposition fractions under optimal conditions. At the beginning of
31 | each year, above- and belowground coarse and fine litter (equal to NPP in the long term) is

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1 added to C_{fast} . Removal of C from the ecosystem by disturbances (e.g. fire) or harvest is taken
2 into account in relation with land use and is described below. The C_{fast} pool is reduced by the
3 annual decomposition fraction (F_f) and a fraction moving from the fast to the slow pool
4 (to_{slow}). Litter quality controls to_{slow} . The maximum decomposition fraction is constrained by
5 temperature, soil humidity, soil acidity, and oxygen availability. The constraints are jointly
6 expressed as a fraction modifying factor (fmf) ranging between 0 and 1 (Fig. 2). The
7 maximum decomposition fraction of the slow pool (F_s) is constrained in the same way as F_f .
8 The inaccessible pool is the fraction of SOC that is frozen, submerged in water, or adsorbed to
9 soil matter and whose decomposition fraction we assume to be negligible under extant
10 conditions within the time perspective of our study. The fraction of C in the inaccessible pool,
11 however, may differ between reference and target conditions when the comparison reflects
12 changes in water-logging or frozen soil. We use a minimum function that considers the
13 constraint of decomposition by a high water table after thawing of permafrost in wetlands.

14 The total amount of C in the fast and slow pool after one year are

$$15 C_{fast,t+1} = (C_{fast,t} + NPP_t) \cdot (1 - fmf \cdot F_f) \cdot (1 - to_{slow}) \text{ and}$$

$$16 C_{slow,t+1} = C_{slow,t} \cdot (1 - fmf \cdot F_s) + C_{fast,t+1} \cdot (1 - fmf \cdot F_s)$$

17 with $C_{fast,t=0} = 0$ and $C_{slow,t=0} = C_0 \cdot af$ or the accessible fraction (af) of the initial total C stock
18 (C_0). NPP is supplied by external models and described below in 'NPP scenarios in the
19 environmental framework'. After several decades, the sizes of the fast and slow pools depend
20 mostly on the amount of annually added C, the decomposition fractions, and the distribution
21 of matter between the fast and slow pools, but little on the initial amount of accessible C for
22 not too small values of fmf ($fmf < 0.1$, see Supplement 3 for a summary equation). Limited
23 substrate availability could reduce decomposition rates (Davidson and Janssens, 2006,
24 Kirschbaum, 2006) but contributed very little to the prediction of existing SOC stocks in an
25 earlier version of the model. Therefore, substrate availability was not included in the final
26 version.

27 The values of the parameters and variables of the decomposition model are controlled by
28 variables in the environmental framework characterizing the physical and biotic environment
29 in a particular location: soil, vegetation, climate, land use.

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1 2.2 The environmental framework

2 The environmental variables and their causal relationships are described by a probability
3 network (Spiegelhalter et al., 1993) using Netica (version 5, Norsys, Vancouver, Canada).
4 Probability networks, also known as Bayesian networks, associate classes (e.g., levels) of
5 each variable, with probability distributions of their occurrence contingent on the occurrence
6 of classes (levels) within other variables. These probabilities can be interpreted as certainties
7 of potential outcomes. Joint probabilities of classes are calculated according to the laws of
8 probabilities, or, in the case of continuous variables, sampled by Monte-Carlo techniques.
9 Probability networks allow the inclusion of the uncertainty or variability of variables and
10 expert knowledge. The networks (one for each of two contrasting NPP submodels in two NPP
11 scenarios) with all probability tables and class borders are supplied in [Supplements 1 and 2](#).
12 [The widths of classes can be thought of as encompassing sub-pixel variation of soil,](#)
13 [vegetation, and environmental variables but we cannot quantify the contribution of sub-pixel](#)
14 [variation to overall certainty of SOC changes.](#)

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15 2.3 NPP scenarios in the environmental framework

16 The strong effect of NPP via litter input on SOC stocks in models is well established and
17 founded on theory (Todd-Brown et al., 2014). The long-term net effect of climate change on
18 NPP and, consequently, litter input, however, is still unclear. NPP might increase because of
19 increasing concentrations of CO₂ in the atmosphere (CO₂ fertilization) but productivity may
20 be limited by the availability of nitrogen or other resources (Gedalof and Berg, 2010, Norby
21 et al., 2010, Todd-Brown et al., 2014). To present the range of the effects of nutrient
22 limitation and CO₂ fertilization we used two contrasting scenarios of future NPP together with
23 climate conforming to the A1B emission scenario (IPCC, 2000). The first scenario, 'limited
24 NPP', represents a change in productivity caused by temperature and precipitation alone, [i.e.](#)
25 [without CO₂ fertilization. This limitation of potential increases](#) could be similar to the net
26 effect of CO₂ fertilization and nutrient-constrained growth. This NPP is based on the
27 empirical NCEAS model (Del Grosso et al., 2008, an extension of the Miami or Lieth model),
28 a function of mean annual temperature, mean annual precipitation, and vegetation type
29 (Supplement 3: Data processing and sources). The second scenario, 'enhanced NPP',
30 represents an increase of productivity due to CO₂ fertilization in addition to changes in
31 temperature and precipitation without limitation of the additional growth by nutrients. This
32 NPP is derived from LPJ, a process-based DGVM (Sitch et al., 2003, Gerten et al., 2004). In

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1 comparisons between the NPP scenarios we keep functional relations (e.g., decomposition
2 fractions, fraction modifying factors, decomposability) and plant type composition within
3 each vegetation type constant.

4 **2.4 Environmental framework structure and parameterization**

5 | The amount of C added to the [fast](#) pool is set equal to the NPP in natural ecosystems and
6 consists of leaf litter, fine and coarse woody debris, and fine and coarse dead roots. C removal
7 with harvested products and higher NPP input by agricultural fertilization must be accounted
8 for in land use effects. We calculated the harvest factor, the mean ratio of NPP after harvest
9 including agricultural fertilization (NPP_i) to NPP of the potential zonal vegetation (NPP_0)
10 | from a global database (Haberl et al., 2007) for each combination of 13 [climatic](#) vegetation
11 zones and six land use classes (zonal, built-up, herbaceous crops, pasture, woody
12 | crops/plantations, wetlands; Supplement 3, Table S4.2 in Supplement 4) for present
13 | environmental conditions. 'Wetlands', [as a special vegetation type and land cover](#), is included
14 in this list for convenience. The harvest factor allowed us to use existing models of NPP_0 and
15 apply it to future conditions. We note that using this procedure glosses over regional
16 differences within vegetation zones.

17 The fraction-modifying factor (f_{mf}) aggregates the effects of temperature, soil moisture,
18 oxygen availability, and soil reaction by multiplication similar to the rate-modifying factors in
19 other decomposition models (e.g., Roth-C, Coleman and Jenkins, 1999). The probability
20 distribution of $f_{mf_{temperature}}$ (Fig. 2a) is a discretization of the equation $\exp(-2.5 +$
21 $0.07 \cdot \text{temperature})$ on laboratory incubation data from several sources (Fig. 2 in Paul et al.,
22 2002). We used laboratory data because we were interested in the effect of temperature in
23 isolation from other variables on the maximum decomposition fraction under optimal
24 conditions. Our discretization of the temperature effect (Fig. 2a) encompasses many other
25 empirical temperature functions that are used in established soil C models like Roth-C,
26 APSIM, or Century (Paul, 2001). In-situ microbial communities might respond to increased
27 constant temperatures with acclimation (Allison et al., 2010). Our approach considers
28 monthly variation of temperatures and aridity and it is unclear from the current literature how
29 strong acclimation is relative to this variability and how much current latitudinal patterns are
30 caused by climate. We assume here that the class widths used in the parameterization of f_{mf}
31 (Fig. 2a) and distinction of monthly temperatures encompass sub-monthly effects of
32 acclimation.

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Gelöscht: accessible (fast and slow)

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Gelöscht: azonal land cover

1 The classification of the moisture effect (Fig. 2b) is associated with Walter & Lieth's (1967)
2 climatic aridity classes. These are arid: $MMP/2 < MMT$, dry: $MMP/3 < MMT$, moist:
3 $MMP > 100$, and mesic: the remainder, where MMT is mean monthly air temperature ($^{\circ}C$) and
4 MMP mean monthly precipitation (mm). In addition, "wet" is used for wetland soils. The
5 shape of the probability distribution associated with the aridity classes corresponds to the
6 probability distribution of the 0.75–1.0 quantile range of laboratory decomposition studies
7 (Paul et al., 2002) and of subsamples of the moisture functions in the decomposition models
8 APSIM (Probert et al., 1998), ED-RAMS (Ise et al., 2008), and ECOSSE (SEERAD, 2007).
9 We selected these models because they included relationships for water-saturated soils. To
10 include seasonal effects, *f_{mf}*s of temperature and aridity were calculated by month, multiplied
11 with each other for each month and averaged (geometric mean) per quarter and then per year.
12 Averaging was necessary to reduce the complexity of the probability network to a level that
13 could be calculated with Netica. Oxygen availability was taken from the Harmonized World
14 Soil Database Supplementary Data and is based on soil drainage and take into account soil
15 type, soil texture, soil phases and topographic position (Fischer et al., 2008). Changes in soil
16 moisture are reflected in the decomposition fraction and the accessible pool fraction. The
17 probability distribution of oxygen availability was set so that completely anaerobic conditions
18 reduce the maximum decomposition fraction to $\frac{1}{7}$ (Freeman et al., 2001).

19 Following the discussion of ECOSSE (SEERAD, 2007), we specified the probability
20 distribution of the soil acidity effect so that decomposition fraction increases from a medium
21 level within the aluminum-buffer pH range (acidic) to optimal within the carbonate-buffer pH
22 range (neutral) and decreases to low as soils become alkaline ($pH > 8.5$; Fig. 2d).

23 Organic matter in the inaccessible C pool decomposes extremely slowly or not at all due to
24 lack of oxygen in water-logged soils, permafrost or adsorption to soil particles (Six et al.,
25 2002). It can have a history of millennia, or, in the case of permafrost, can date back to the
26 last interglacial period. We determined this quasi-constant pool as the fraction of SOC that is
27 inaccessible in the top 1 m as the maximum of the fraction that is permanently water-logged
28 and the fraction that is permanently frozen, plus the fraction of the remaining C protected by
29 soil particle adsorption. We set the fraction of water-logged soil to 0.9–1.0 with 80%
30 probability for wetlands and to 0.0–0.1 with >94% probability for other land cover types
31 (Table S4.6 in Supplement 4). The fraction of permafrost is calculated as a function of the
32 number of days in a year with mean daily temperature $> 0^{\circ}C$ (degree days, DD0), 1–

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Gelöscht: ary material

1 0.02· $\sqrt{DD0}$ (Anisimov et al., 2002). The fraction of SOC protected by particle adsorption is
2 calculated [for mineral soils](#), roughly following the SOCRATES model (Grace et al., 2006), as
3 (0.14·CEC + 40)/100 if CEC<100 mmol/kg, else (0.04·CEC+50)/100 with a maximum of 1.
4 [The CEC of soils with >20% organic carbon content was set to 0.](#)

5 The decomposability of litter that controls the fractions of the slow and fast C pools depends
6 on plant type and indirectly on vegetation type and land use (Tables S4.4 and S4.5 in
7 Supplement 4). The classification of plant types and their association with decomposability is
8 our interpretation of meta-analyses of leaf litter (Cornwell et al., 2008) and wood
9 decomposition (Weedon et al., 2009). We estimated, based on studies in many types of forests
10 (Rodin and Bazilevich, 1967, Laiho and Prescott, 2004, Rice et al., 2004, Steinaker and
11 Wilson, 2005), that [above- and belowground fine \(leaf and fine roots respectively\) and above- and
12 belowground coarse \(coarse woody debris and coarse roots respectively\) litter](#) contribute on average
13 equal proportions to litter input entering forest soils. About 10% of the C allocated to roots
14 may be lost as easily decomposable exudates (van Hees et al., 2005). This is implicitly
15 reflected in the fraction of total litter attributed to the high and very high decomposability
16 class and its fraction (not) going to the slow C pool (Table S4.5 in Supplement 4). The
17 proportions of plant types within vegetation types (Table S4.2 in Supplement 4) are based on
18 those reported in Sterling & Ducharme, proportions of vegetation classes in the Global Land
19 Cover Characterization (Loveland et al., 2000) – Global Ecosystem legend (plantations),
20 USGS legend (tundra, wetlands), and personal experience for non-vascular plants.

21 Zonal vegetation of target conditions are linked to the reference zonal vegetation by transition
22 probabilities for each vegetation type (Gonzalez et al., 2010). Probability distributions of
23 target land use are contingent on reference land use, target temperature, and target aridity. We
24 compared crop and pasture land use maps for 2000 and 2075 (de Noblet-Ducoudré and
25 Peterschmitt, 2008) to calculate probabilities of changes among land use classes for each
26 cross-classification of reference temperature and aridity. We modified these probabilities and
27 assigned probabilities for land use changes among other classes according to a set of rules
28 based on our experience (Table S4.3 in Supplement 4). [These land use changes are thus
29 hypothetical and constrained mostly by climate. Wetlands, however, are set to remain
30 wetlands with a very high probability \(≥97%\).](#)

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Gelöscht: leaf litter and fine root litter on the one hand and dead wood (above- and belowground) on the other hand

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Gelöscht: ary material

1 2.5 Calibration

2 The decomposition model was calibrated at the global scale (using half of the data points for
3 training and the other half for validation) by systematically varying the decomposition
4 fractions F_f and F_s in steps of 0.05. Smaller steps produced hardly perceivable changes to the
5 output. We selected the combination of decomposition fractions so that the HWSD-SOC
6 stock classes across all pixels were predicted most often by the most probable reference SOC
7 stock class. This resulted in maximum decomposition fractions $F_f = 0.75$ —corresponding to
8 a decomposition rate $k = -\log_e(1 - F_f) = 1.4$ — and $F_s = 0.35$ ($k = 0.4$). Using these
9 decomposition fractions and NPP_0 (Haberl et al., 2007), the model correctly predicted 78% of
10 all HWSD-C stock classes (Fig. S3.6 in Supplement 3). Further details are provided in
11 Supplement 3.

12 2.6 Presentation of results

13 All variables in the model were associated with a frequency distribution that affected the
14 certainty of changes in SOC stocks. This paper focuses on the certainty of changes in SOC
15 stocks. Therefore, we report and discuss the probability-weighted means of their distributions.

16 SOC stocks presented in this paper are averages across SOC stock classes (class borders: 0, 2,
17 5, 10, 15, 20, 30, 60, 80, 100 kg/m²) weighted by class probability. Changes in SOC stocks
18 are expressed as half the mean of the frequency distribution of the differences between the
19 reference and target SOC stock distributions throughout this paper. Using the half puts the
20 numerical value of changes more in line with the gradual change between reference and target
21 conditions as projected by GCM-DGVM combinations. We express the certainty of gains or
22 losses as the certainty of the difference between reference and target SOC stock being >0. We
23 call changes associated with a certainty $P > 0.67$ ‘fairly certain’ and changes with $P > 0.75$
24 ‘highly certain’. 50% certainty in this context would imply that losses and gains are equally
25 certain. These certainties are not expressions of statistical significance but represent the
26 likelihood that a certain outcome (or distribution of outcomes) might be or become true given
27 the assumptions and width of classes of the contributing variables. All reported SOC stocks
28 from our simulations are standardized to the SOC stocks of the Harmonized World Soil
29 Database, HWSD, as processed by Köchy et al. (2014) (Supplement 3, Fig. S3.3).

30 For examination of specific land use changes we examined individual pixels (Table S5.1, Fig.
31 S5.1 in Supplement 5) including those used by Jones et al. (2005) and Schaphoff et al. (2006).

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1 3 Results

2 3.1 Agreement of steady-state with HWSD stocks

3 We compared the SOC stocks for reference conditions to the SOC stocks calculated from
4 HWSD. We did not use observed time series of SOC for validation because our study is
5 aimed at assessing (un)certainties of effects and assumes constant conditions until a defined
6 end-point. Our SOC stocks are the average of the class mean weighted by class probability.
7 Since the ranges of SOC stocks in the higher classes were broader than those in the lower
8 classes (see Methods: Presentation of results), mean values tended to overestimate HWSD-
9 SOC stocks. Almost half (47%) of reference stocks were within $\pm 50\%$ of the HWSD stock;
10 78% of reference stocks were within $-50\%/+100\%$ of the HWSD stock. Nonetheless, absolute
11 differences were small (Fig. S3.6 in Supplement 3). In more than half of all cases (53%) the
12 absolute difference was $< |\pm 5| \text{ kg C/m}^2$ and in 88% of the cases the difference was $< |\pm 10| \text{ kg}$
13 C/m^2 . In our approach we use classes (i.e. ranges) of values to reflect, amongst others,
14 uncertainty in measurements and local variation. This uncertainty affects the degree of
15 agreement with HWSD-SOC stocks. If we had used single, weighted averages of NPP_t , f_{mf} ,
16 *accessible fraction*, and t_{slow} then 55% of simulated C stocks would have been within $\pm 25\%$
17 of HWSD stock and 79% within $\pm 50\%$ of HWSD C-stock (or $r_{\text{pearson}} = 0.89$) with the absolute
18 difference being $< |\pm 2| \text{ kg C/m}^2$ in 55% of all cases and $< |\pm 5| \text{ kg C/m}^2$ in 89% of all cases. The
19 greatest sensitivity of the total reference SOC stock was, in decreasing order, to NPP_t and
20 NPP_0 , followed by vegetation zone, HWSD-SOC, and f_{mf} (Supplement 3).

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21 3.2 Effect of climate change on environmental factors

22 Climate change till the end of the century (i.e. changes in monthly temperatures and aridity) is
23 reflected in changes of the fraction modifying factor (f_{mf}) and the probabilities of shifts in
24 vegetation zone and land use with secondary effects via plant type composition,
25 decomposability, and proportion of C input going directly to the slow pool. In general, the
26 differences in f_{mf} between reference and target conditions were small (Fig. 3b). Strong
27 increases were confined mostly to relatively arid tropical regions, where increases in winter
28 precipitation were strong.

29 Increases in the depth of the active layer of permafrost were $< 20 \text{ cm}$ in most locations.
30 Increased thawing depth of 20–30 cm was projected only for the central Asian mountain

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Gelöscht: NNP₀

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1 ranges. Although permafrost soils were projected to thaw deeper, not all thawing regions were
2 exposed to decomposition of more organic matter because the C_i at least in mineral soils, was
3 stabilized by CEC.

4 Decomposability of litter varied between around 0.3 and 0.6 relative units, but changes in
5 decomposability between reference and target conditions were comparatively small
6 (Supplement 4, Fig. S4.1). In the limited NPP scenario the low increase of NPP had little
7 effect on the plant type distribution so that changes of decomposability were within ± 0.05
8 units. In the enhanced NPP scenario plant type distributions shifted more strongly so that
9 changes of decomposability ranged between -0.2 and $+0.1$ units. The greatest decreases
10 (causing higher SOC stocks) occurred in tundra where the proportion of woody plants was
11 projected to increase by external models. The greatest increases of decomposability occurred
12 (1) in the southern boreal forest where deciduous trees replaced evergreen trees and (2) in
13 those parts of the tropical forests with a high probability that pristine forest is converted to
14 cropland or perennial plantations.

15 3.3 Effect of climate and land use change on SOC stocks under contrasting 16 NPP scenarios

17 In the limited NPP scenario, NPP_t changed little by the end of the century (Fig. 4a). Most
18 notable were extensive increases in the boreal forest and scattered losses in tropical regions.
19 Under limited NPP conditions, global SOC mass might decrease ($P > 0.5$) by a net mean of 21
20 Pg due to the effect of projected climate and land use change (Fig. 5a). At mid-latitudes
21 (35°N – 65°N) gains were greater than losses, whereas losses were greater than gains between
22 30°N and 30°S . In most locations the certainty of changes was low ($P < 0.67$) (Fig. 6a). If we
23 consider only SOC changes at a certainty level ≥ 0.75 , the global change of SOC mass is 0 Pg
24 (Fig. 5a), i.e. gains and losses were balanced. Patches with highly certain losses occurred in
25 high elevations of the northern Andes, New Guinea, and eastern central Africa. Locations
26 with highly certain gains were high elevations in the southwestern USA, the highlands of
27 southern Africa, and the central Asian mountain ranges.

28 In the enhanced NPP scenario, NPP_t increased in almost all regions. The increases were
29 greatest in the humid tropics and higher altitudes (Fig. 4b). The global SOC mass (0–1 m)
30 might increase ($P > 0.5$) by a net mean of 55 Pg due to climate change, land use change, and
31 CO₂ fertilization (Fig. 5b). If we consider only changes at a certainty level ≥ 0.75 (Fig. 6b), the

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1 global net mean gain of SOC is 11 Pg (Fig 5b). Regions with highly certain losses and means
2 of 2–10 kg/m² were few and small, representing high elevations in the northern Andes,
3 eastern Central Africa, and New Guinea. Highly certain gains with means of 2–10 kg/m²
4 occurred in arid higher elevations of southeastern North America, southern Africa, central
5 Asia, and scattered in other highlands.

6 We located ‘hotspots’ of SOC vulnerability where losses occurred across both NPP scenarios.
7 There was, however, little overlap across both NPP scenarios. In both NPP scenarios, SOC
8 stocks are fairly certain to increase in northern Labrador (Canada) and the Chukotsky
9 peninsula (most western tip of Siberia), whereas SOC stocks are fairly certain to decrease in
10 parts of the mountain ranges of the northern Andes, in the Ethiopian and eastern-central
11 African highlands, and in the mountain range of New Guinea (Fig. 5c). There was no
12 discernable pattern of coincidence with current land use. In the tropics 23% of the 169 pixels
13 with losses were located below 500 m altitude, 19% within 500-1000 m altitude, and 58%
14 within 1000-2500 m altitude, 84% of the pixels were located on ridged terrain (Fig. 5c). Ten
15 of the 23 pixels with gains in the tropics (43%) were located at altitudes >2500 m. Pixels
16 outside the tropics showed no discernable patterns with topography.

17 **3.4 Effect of climate change with enhanced NPP by vegetation zone and by** 18 **land use**

19 In each vegetation zone the median net change of C stocks across all pixels was positive (Fig.
20 S4.3 in Supplement 4). For each vegetation zone as a whole, the direction of net change is
21 uncertain due to the great environmental heterogeneity within each zone. Most changes
22 between land use types across vegetation zones were similarly uncertain because of the great
23 heterogeneity involved. Conversion of cropland to wetland, however, has a high certainty of
24 C stock gains with a mean of 3 kg C/m². Similarly, conversion of wetlands to crops is highly
25 certain to incur losses of C with a mean of 5 kg C/m² across vegetation zones. Conversion of
26 wetlands to pastures or plantations are also fairly certain to incur losses.

27 In order to reduce the heterogeneity in the assessment, we also considered land use changes
28 within vegetation zones. The same patterns as reported above occurred. In addition,
29 conversions from zonal vegetation to croplands were found to fairly certainly incur losses in
30 temperate vegetation zones and tropical forests and woodlands. In contrast, conversion from
31 zonal vegetation to cropland in hot deserts is fairly certain to incur gains with a mean of 4 kg

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1 C/m². This effect arises because the imposed land use change assumes strong increases in C
2 input in a region with natural low productivity. Similarly, re-conversion of cropland to zonal
3 vegetation is fairly certain to incur gains in C stocks in temperate forests and tropical
4 deciduous and evergreen forests with means ranging between 2 and 3 kg C/m². Obviously, the
5 opposite was fairly certain for hot deserts.

6 By inspection of individual pixels we reduced the spatial heterogeneity as far as possible in
7 our approach (Table S5.2 in Supplement 5). A general picture emerged. Changes with fairly
8 or high certainty were associated with strong increases in NPP_t.

9 Almost all non-wetland tundra is currently not subject to land use. Under target conditions,
10 15% of the tundra is projected to be used as boreal forest plantations. Changes in *fmf* were
11 small and increase in NPP₀ balanced or overcompensated losses of thawed fossil C. Increases
12 in NPP₀ and consequently SOC stocks were projected to be higher and gains fairly certain in
13 alpine tundras of central Asia. In many arctic locations, SOC stocks would increase fairly
14 certainly if the permafrost soil turned into wetlands.

15 Boreal regions would be increasingly used as timber plantations and probably as arable land.
16 Timber harvesting of formerly pristine boreal forests is not likely to decrease SOC stocks.
17 Tree removal for cropping, however, reduces SOC stocks fairly certainly in some pixels with
18 mean losses of up to 5 kg/m² compared to reference conditions. Creation of wetlands in boreal
19 forests, e.g. by thermokarst processes, would fairly certainly increase SOC stocks with a mean
20 gain of 3 kg/m².

21 In some pixels of temperate grasslands (steppes) in eastern Asia the projected increase in NPP
22 was high and increase in SOC stock in grazed steppes (up to 6 kg/m²) was fairly certain.
23 Where temperate grasslands are currently used as arable land and were used for pasture or left
24 to return to zonal vegetation, SOC stocks would increase with fair or higher certainty.
25 Conversion of cultivated steppe (perhaps former wet depressions, e.g., prairie potholes) to
26 wetlands would fairly certainly increase SOC stocks by up to 5–6 kg/m².

27 SOC stocks in pixels with temperate forests also echoed the general picture that higher inputs
28 were associated with fairly or highly certain gains, so that conversions to cropland or pastures
29 often incurred losses (e.g. 5 kg C/m²) and land use changes to woody vegetation incurred
30 fairly or highly certain gains of similar size. Pixels where changes in *fmf* were rather high for
31 the vegetation zone showed that this was not sufficient for making decreases fairly certain if
32 the increase of NPP_t was not also low.

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1 In dry tropical and subtropical regions encompassing desert, grassland, shrubland, and
2 savanna, projected increases in productivity of zonal vegetation were high, generally entailing
3 highly certain increases in SOC stocks with means in the range of 2–6 kg/m². In several
4 shrubland pixels, zonal vegetation was projected to suffer from strong decreases in NPP,
5 resulting in fairly certain decreases, especially when the land use simultaneously changed to
6 crops or pasture.

7 Pixels in tropical forest zones were characterized by projected changes in zonal NPP between
8 –0.07 and +0.72 and increases in *f_{mf}* between 0 and 0.22. In locations where *f_{mf}* increased
9 strongly, reductions in NPP input due to land use change acerbated the loss of C from soil.
10 Losses due to cropping or conversion to pasture were highly certain in most cases with mean
11 losses between 2 and 10 kg C/m².

12 **4 Discussion**

13 We assessed the certainty of changes in SOC stocks due to climate and land use change using
14 a framework that explicitly considers the frequency distribution of values of controlling
15 variables of decomposition processes. The greatest changes in mean SOC stocks after 75
16 years globally were due to absolute changes in NPP and thus C input to the soil. The effects
17 of two contrasting global models of NPP on changes in soil C mass differed in sign (Fig. 5),
18 showing the great importance of improving projections of NPP, especially with respect to N
19 limitation and CO₂ fertilization. Direct climate effects on mean decomposition fractions via
20 temperature and moisture were greatest at the drier edge of the tropics (Fig. 3). The reason is
21 that increased precipitation throughout the tropics (as projected by ensemble GCM results)
22 had a greater effect on decomposition fractions in the drier regions than in the humid tropics.
23 The global patterns of SOC stock changes in our study and the enhanced NPP scenario agree
24 with results obtained by mechanistic earth system models (Todd-Brown et al., 2014) and
25 underlines the validity of our modelling approach. At high latitudes the increase in
26 temperatures were considerable, but the absolute effect of the increase on decomposition
27 fractions remained small. The slight negative effect on SOC stocks was matched or surpassed
28 by greater input from NPP. In warm regions, increases in temperature entailed relatively great
29 decomposition fractions whose effects on SOC stocks were not necessarily matched by
30 greater input from NPP.

31 Our results based on the limited NPP scenario (Fig. 5a) may be more likely if future increases
32 of NPP are limited by nutrient availability despite CO₂ fertilization (Norby et al., 2010). a

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1 | [concern raised also in a recent review earth-system models \(Todd-Brown et al., 2014\)](#). The
2 results based on enhanced NPP may become more likely if anthropogenic N deposition
3 increases and alleviates nutrient limitations of growth (Hyvönen et al., 2007). The probability-
4 weighted mean change of global SOC of 11 Pg (at a level of 75% certainty) in the elevated
5 NPP scenario in our study, with consideration of wetlands, permafrost, and land use,
6 corresponds to the lower end of the range of 15–100 Pg indicated by another study using
7 frequency distributions for parameters (Hararuk et al., 2014) when both results are expressed
8 as a fraction of the total SOC mass derived from the reference database used in each study
9 (1061 and 1567 Pg).

10 Tropical mountain forests showed losses across both NPP scenarios and emerged as hotspots
11 of SOC vulnerability. Most of these hotspots were characterized as zonal vegetation. Total
12 modelled SOC loss in tropical hotspots (1 Pg, both NPP scenarios) comprised a small portion
13 of the whole tropical loss (11 Pg, limited-NPP scenario; 6 Pg, enhanced-NPP scenario) on 2%
14 of the tropical land area.

15 SOC losses in identified hotspots were highly certain. Pixels with gains were less consistent
16 among NPP scenarios. Only the easternmost tip of Siberia emerged as a hotspot of certain
17 gains.

18 The low certainty of SOC changes shown in this study reflects the limited certainty of the key
19 variables in the terrestrial C cycle and their future changes, especially current SOC stocks,
20 NPP_t , and decomposition fractions. The uncertainty is unfortunately greatest for the location,
21 spatial extent, and actual stock of C-rich soils (Köchy et al., 2014). Our study includes only
22 part of the uncertainty in NPP_0 expressed by the variability among different global climate
23 models linked to different vegetation models (Schaphoff et al., 2006, Sitch et al., 2008). This
24 uncertainty is exacerbated by the need to estimate the harvest factor for future conditions.
25 Currently, human activity reduces global NPP_0 by 24% (Haberl et al., 2007). This fraction can
26 be expected to increase in the future with increasing global populations. The uncertainty
27 regarding the effect of temperature and moisture on decomposition fractions at the global
28 scale and at long time scales is still great (Kirschbaum, 2006). Reported large-scale
29 correlations between temperature or moisture and decomposition fractions (or rates) have
30 been suggested to be spurious due to differences in litter quality and moisture along latitudinal
31 gradients (Giardina and Ryan, 2000). This view has been contested (Davidson et al., 2000).
32 Our model framework on the one hand supports a strong positive association between litter

1 quality and aridity across vegetation zones. On the other hand, it shows only a weak
2 association between litter quality and mean annual temperature and thus latitude. At the
3 global scale, temperature sensitivity may be lower ($Q_{10}=1.4-1.9$, Hararuk et al., 2014, Ise and
4 Moorcroft, 2006) than generally assumed from short-term incubation studies ($Q_{10}\geq 2$) and that
5 maximum decomposition occurs at greater soil moisture than assumed in most models (Ise
6 and Moorcroft, 2006). If temperature sensitivity at the global scale is indeed lower than
7 generally assumed, decomposition fractions in warm regions would not increase as much as
8 projected and tropical SOC stocks would decrease less strongly.

9 Differences in global climate models and vegetation models cause spatial variation in
10 projected distributions of plant types (Alo and Wang, 2008, Gonzalez et al., 2010). In
11 addition, global vegetation models do not account for adaptation of species in response to
12 climate change. Our sensitivity assessment showed that plant types had an overall small effect
13 on decomposition fractions via litter quality. This was mostly due to the fact that the woody
14 fraction of NPP is the strongest predictor of litter quality at the global scale but did not change
15 drastically in most places. The moderate sensitivity of SOC stocks to plant types suggests that
16 our conclusions about changes of SOC stocks and their certainty are robust to uncertainties in
17 the global distribution of plant types.

18 Changes in SOC stocks after 75 years due to changes in land use were on average small
19 because the average probabilities of land use change per vegetation zone that we applied to
20 each pixel were low. This effect is also exemplified by a retrospective study where drastic
21 deforestation of Amazonian forest only caused a net decrease of 0.5% of C stocks across the
22 whole study area (Holmes et al., 2006). Quantitative, spatially explicit projections of the
23 change of land use towards the end of this century require socio-economic models linked to
24 vegetation models, which adds another layer of complexity and uncertainty. Instead, we
25 examined different prescribed land use changes in individual locations. For tree-dominated
26 ecosystems SOC stocks decreased in the order zonal > plantation > pasture > annual crops,
27 emphasizing that C input is one of the most important driving variables for predicting the net
28 rate of SOC change; the greater the remainder after harvest, the greater the increase (or the
29 smaller the losses). Draining wetlands is exposing SOC and was linked to considerable and
30 highly certain C-losses in all vegetation zones. Our model suggests that agroforestry
31 producing sufficient C input or wetland cropping (rice paddies) may be ways to conserve
32 SOC and extract food at the same time. Our modelling results agree in trend with reviews on

1 land use change effects in temperate and tropical regions (Don et al., 2011, Poeplau et al.,
2 2011). In contrast, our results do not show the great increases (>100%) in SOC stocks after
3 conversion from cropland to grassland or forest in temperate zones and our projected
4 increases for land use changes in tropical regions are greater (by a factor of 1.5–2) than those
5 reported by Don et al. (2011).

6 The goal of our assessment of SOC stocks was to identify patterns of fairly and highly certain
7 changes of SOC at the global scale. The SOC stocks and their changes simulated by our
8 model were within the wide range of outcomes produced by different combinations of global
9 circulation models (Schaphoff et al., 2006), global vegetation models (Sitch et al., 2008), and
10 different soil modules (Yurova et al., 2010) and several earth system models (Todd-Brown et
11 al., 2014). The delicate balance between higher NPP and higher decomposition rates as the
12 main control of the gain or loss of C stocks that emerged from the aforementioned global
13 studies was confirmed by our assessment. In addition, our study showed that the certainty for
14 strong changes in SOC stocks is rather low.

15 Increasing aridity with climate change could substantially reduce SOC stocks in tropical
16 peatlands (Li et al., 2007). Our framework allows attaching a probability to this. Assuming an
17 SOC stock of 30 kg/m² in evergreen tropical forest with 0.8–1.0 kg/yr NPP, a water table <20
18 cm below ground and average annual temperature and aridity, our model projects a
19 distribution of SOC stock with a mean of 24 kg/m². If precipitation decreased so that the
20 water table decreases to >20 cm, the potential C loss due to higher decomposition fractions
21 would not be balanced by the higher NPP of 1.0–1.2 kg/yr projected for future conditions.
22 The distribution of potential net losses has a mean of 3 kg/m², with a 68% certainty that the
23 losses are > 2 kg/m².

24 In boreal and arctic regions we found few hotspots of vulnerability because increases in
25 decomposition fractions and exposed frozen soil were smaller than increases in productivity.
26 Our assessment agrees with ensemble results of ten global climate models (Qian et al., 2010)
27 incorporating CO₂ fertilization of NPP. The ensemble results, however, indicated that
28 increases in NPP would level off towards the end of the 21st century while C emissions would
29 continue increasing, causing a net source in northern high latitudes in the following century.
30 Loss of C stocks could be greater than simulated by our model because of additional heat
31 produced by microbial activity (Khvorostyanov et al., 2008) and if permafrost thawing
32 conforms more to Khvorostyanov et al.'s algorithm from a global circulation model (Poutou

1 et al., 2004) than to the algorithm used by us (Anisimov et al., 2002). Another study found
2 higher C emissions in some locations in the permafrost region that were not matched by
3 increased NPP. It is however, unclear, if this local observation is representative for the
4 heterogeneous thermokarst landscape (Kuhry et al., 2010), where ponds from meltwater might
5 limit C emissions (Moore and Knowles, 1989, Rouse et al., 1997). Spatially integrating
6 measurements using eddy-flux methodology over a c. 10-ha area in a Siberian tundra site
7 (70°50'N, 147°30'E, Parmentier et al., 2011) suggested that ecosystem C uptake would be low
8 under climate warming, which is also projected by our assessment in both scenarios.

9 The accumulation and preservation of high SOC stocks is to a large extent due to conditions
10 of low oxygen availability in wetlands. Existing global wetland maps show great
11 heterogeneity in wetland extent and classification (Lehner and Döll, 2004, Köchy and
12 Freibauer, 2010). For the purpose of soil C modelling, a (global) map indicating water table
13 depth (and its variability) within the top 1m may be more suitable than the combination of
14 three indices, the index of O₂ constraint, the 'wet' moisture class, and water-table estimates
15 per land use class, that we used in the absence of such a map. Such a map might be achievable
16 by assimilation of remote sensing (Finn et al., 2011) in wetland models (Fan and Miguez-
17 Macho, 2011) and could provide the base to incorporate effects of aridity in wetlands (Ise et
18 al., 2008). Changes in aridity and sea level rise may create new and vast wetland areas. In
19 arctic regions, wetland area might increase due to thawing of permafrost soil, snowmelt, and
20 flooding (Rouse et al., 1997). These wetland dynamics are commonly not taken into account
21 in global C models. The probability tables used in our model can be a starting point for such
22 global modelling activities.

23

24 **5 Conclusions**

25 Our assessment showed in a spatially explicit way the great uncertainties associated with
26 potential SOC stock changes globally. Changes of SOC had a high certainty only in a few
27 locations. In general, the strength of changes did not correlate with the certainty of changes.
28 Therefore, conclusions about local and global changes would differ depending on what level
29 of certainty one accepts for accounting changes. This aspect has been considered only via
30 ensemble runs of models but not within models so far. Assessments of uncertainties within
31 models could direct future research. The fertilization effect of CO₂ on NPP in the long-term
32 and its variation at the global scale is one of the major uncertainties. Global maps of current

1 SOC stocks are derived from soil surveys dating as far back as the 1920s and complete
2 information for C-rich soils comes from few soil profiles. Up-to-date records of up-to-date
3 location, extent, and water table variation of wetlands at the global scale are incomplete. The
4 same holds for permafrost and the active layer. Monitoring of these variables are crucial for
5 decomposition models, assessments of global SOC stocks, and certainty of changes.

6

7 **Author contributions**

8 MK devised the approach, designed and carried out the analyses and wrote the manuscript,
9 discussions with AD, MvdM and AF greatly influenced the parameterization of the
10 environmental framework and design of the analysis, AF suggested the topic.

11

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1 Fig. 1. Network design. *fmf*: decomposition fraction modifying factor, *F*: decomposition
2 fraction. Boxes with thick edges indicate directly supplied information. Boxes with dashed
3 edges (on the target side) indicate values copied from the reference side. Shaded boxes
4 indicate dependent variables.

5

6 Fig. 2. Probability distribution of four fraction-modifying factors (*fmf*). Box width within each
7 class of decomposition fraction controlling variable (x-axis) is proportional to probability of
8 the class of the fraction modifying factor. O₂ constraint labels: no, moderate, severe, very
9 severe, rock or bare, permafrost, wetland. Note that the y-axes are not linear.

10

11 Fig. 3. Decomposition-fraction modifying factor (*fmf*) under reference climatic conditions (a)
12 and difference in *fmf* between reference and target conditions (b). *fmf* summarizes the effects
13 of temperature, humidity, soil reaction, and oxygen availability on the decomposition fraction.

14

15 Fig. 4. Difference in NPP_t between target (future climate and land use) and reference (current)
16 conditions using a) the NCEAS model (limited NPP) or b) the LPJ model (enhanced NPP) for
17 NPP₀.

18

19 Fig. 5. Changes of soil organic carbon stocks and masses using (a) limited NPP and (b)
20 enhanced NPP. (c) consensus: locations where changes $\geq |1 \text{ kg/m}^2|$ in both scenarios, overlaid
21 on topography.

22

23 Fig. 6. Certainty of changes of SOC stocks using (a) limited NPP and (b) enhanced NPP and
24 (c) consensus: locations where certainties of both scenarios are > 0.66 ($P_{\text{limited}} > 0.66$ &
25 $P_{\text{enhanced}} > 0.66$).