

# COMPARING THE PERFORMANCE OF THREE LAND MODELS IN GLOBAL C CYCLE SIMULATIONS: A DETAILED STRUCTURAL ANALYSIS

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## ABSTRACT

Land models are valuable tools to understand the dynamics of global carbon (C) cycle. Various models have been developed and used for predictions of future C dynamics but uncertainties still exist. Diagnosing the models' behaviors in terms of structures can help to narrow down the uncertainties in prediction of C dynamics. In this study three widely used land surface models, namely CSIRO's Atmosphere Biosphere Land Exchange (CABLE) with 9 C pools, Community Land Model (version 3.5) combined with Carnegie–Ames–Stanford Approach (CLM-CASA) with 12 C pools and Community Land Model (version 4) (CLM4) with 26 C pools were driven by the observed meteorological forcing. The simulated C storage and residence time were used for analysis. The C storage and residence time were computed globally for all individual soil and plant pools, as well as net primary productivity (NPP) and its allocation to different plant components' based on these models. Remotely sensed NPP and statistically derived HWSD, and GLC2000 datasets were used as a reference to evaluate the performance of these models. Results showed that CABLE exhibited better agreement with referenced C storage and residence time for plant and soil pools, as compared with CLM-CASA and CLM4. CABLE had longer bulk residence time for soil C pools and stored more C in roots, whereas, CLM-CASA and CLM4 stored more C in woody pools because of differential NPP allocation. Overall, these results indicate that the differences in C storage and residence times in three models are largely because of the differences in their fundamental structures (number of C pools), NPP allocation and C transfer rates. Our results have implications in model development and provide a general framework to explain the bias/uncertainties in simulation of C storage and residence times from the perspectives of model structures. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: model structure; C pool; C partitioning coefficients; C transfer coefficients; C storage; C residence time

## INTRODUCTION

Soil as an integral part of terrestrial ecosystem regulates the biogeochemical cycles and offers wide services to human-kind (Keesstra *et al.*, 2012; Berendse *et al.*, 2015; Brevik *et al.*, 2015). Changes in the soil system largely affect the global carbon (C) cycling (Bruun *et al.*, 2015; Pallavicini *et al.*, 2015). The increasingly complex land models have become major tools for understanding the C cycle (Luo *et al.*, 2003; Zhou & Luo, 2008; Luo & Weng, 2011). These models use different assumptions and formulations in representing the processes that control C dynamics. While such complexity is often justified during model development, quite often it hinders model assessment and intercomparison. Thus, there is great diversity in model-based C cycle results. For example, the Coupled Model Intercomparison Project (C4MIP) reported that the C uptake varied from 100 to 800 GtC in response to doubled CO<sub>2</sub> concentration among 11 climate models over a period of 1850–2100 years (Friedlingstein *et al.*, 2006; Arora *et al.*, 2011). Models are conventionally analyzed by intercomparing their output, as well as with reference data sets (Wang *et al.*, 2011a,

2011b). Although such intercomparisons are necessary, they still lack the adequate information in attributing the sources of variations to their root causes. This shortcoming can be improved by gaining better understanding of the models' fundamental structural differences and the parameters that control C cycle.

In most terrestrial ecosystem models, photosynthetically fixed C by plants is partitioned into several plant tissues (leaf, root, stem) followed by transfer to litter and soil pools. The plant tissues can live from several months (e.g. leaves and fine root) to hundreds of years (e.g. wood). The microbial community partially decomposes the dead plant materials (i.e. litter) into soil organic matter (SOM), which can store C for hundreds and thousands of years before it is respired back into the atmosphere. Decomposition of C compounds is controlled by the physiochemical properties of C substrate, temperature and moisture conditions (Davidson & Janssens, 2006; Wellock *et al.*, 2013). Although significance progress has been made on understanding of C cycle during recent decades, determining the biases of different processes, e.g. C transfer rates and C losses through reparations, is still challenging (Luo *et al.*, 2003).

In case of C transport and storage, it is uncertain whether the discrepancies among the models arise from differences in photosynthetic C influx, model structure (including

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number of C pools and their connecting structure) and/or model parameterization (including transfer coefficients) (Luo *et al.*, 2001; Rafique *et al.*, 2015). Previous research has shown that the variation in modeled soil C stocks can be explained by the differences between net primary productivity (NPP) simulation, decomposition rate and temperature sensitivity (Todd-Brown *et al.*, 2013; Todd-Brown *et al.*, 2014). However, this work did not disentangle the effects of the pool structure or parameterization regarding bulk decomposition rate. To overcome such limitations in intercomparison studies, detailed structural analysis of models would need to be used.

In this study, we performed a detailed structural analysis for three widely used land models (CABLE, CLM-CASA and CLM4) to examine their similarities and differences for handling C exchange, storage and residence time. Specifically, we first evaluated the models' performance against the satellites based observed global C storage and residence time. Second, we decomposed the complex models into traceable components of C storage and residence time in order to examine the underlying differences in the three models' structures. Third, we estimated the C partitioning and transfer coefficients as well as their potential contribution in determining the C storage and residence time.

## MATERIAL AND METHODS

Most of the land models simulate four common properties of C cycle: (i) photosynthesis as the common starting point of C flow in an ecosystem; (ii) partitioning of assimilated C into different vegetation compartments; (3) C transfer among different pools; and (4) first order decay of litter and SOM. Mathematically, these basic properties can be expressed as:

$$\begin{cases} \frac{dX(t)}{dt} = AX(t) + BU(t) \\ X(0) = X_0 \end{cases} \quad (1)$$

Where  $X(t)$  is a vector representing the C pool sizes,  $A$  is the C transfer matrix,  $U$  is C input via photosynthesis,  $B$  is partitioning coefficients and  $X(0)$  is the initial value of the C pool. The  $A$  matrix is conditioned by environmental scalar (temperature and water/precipitation) values (Luo *et al.*, 2012). In these equations, long-term ecosystem C storage is the product of C input for each pool multiplied by its residence time (Luo *et al.*, 2003).

### Three Global Land Models

We used three land surface models in this study. First, the CABLE model, which is an Australian land surface model used to simulate land atmospheric exchanges (Kowalczyk *et al.*, 2006). Its C module is evolved from Carnegie-Ames-Stanford Approach (CASA) and C-Nitrogen-Phosphorous (CNP) (Wang *et al.*, 2010; Wang *et al.*, 2011a, 2011b). The CABLE model has three plant C pools (leaf, root and wood), three litter pools (metabolic, structural

and coarse woody debris (CWD)) and three soil pools (fast, slow and passive SOM). In CABLE, the allocation of NPP into plant pools is determined by the availability of light and water (Xia *et al.*, 2013). The C transfer is determined by the lignin/nitrogen ratio from plant to litter and the lignin fraction from litter to soil pools. The turnover time ranges from several months to thousands of years for different pools of C.

Second, the Community Land Model version 3.5 (CLM-CASA) model combines the biogeophysics of the CLM with CASA biogeochemistry module (Doney *et al.*, 2006). This model has three plant C pools (leaf, fine root and wood), six litter pools (surface structural, surface metabolic, surface microbial, soil structural, soil microbial and CWD) and three soil pools (soil microbial C, slow and passive SOM). In CLM-CASA, the allocation of NPP into plant pools is determined by the availability of light, water, nitrogen and changes in atmospheric C dioxide ( $CO_2$ ) concentration (Friedlingstein *et al.*, 1999). The C transfer among pools is sensitive to climate conditions. The turnover time ranges from several months to hundreds of years for different pools.

Third, the CLM4 model is an upgraded version of CLM (Gent *et al.*, 2011). The CLM4 represents a significant enhancement in model structure and model parameterizations based on the terrestrial biogeochemistry model Biome-BGC (Thornton & Rosenbloom, 2005; Thornton *et al.*, 2009). This model has six plant pools (leaf, live stem, dead stem, live coarse root, dead coarse root and fine root pools), four litter pools (labile, cellulose, lignin and CWD) and four soil C pools (fast, medium, slow and very slow). Each of plant pools has two corresponding C storage pools for short and long term storage. There is no distinction between surface and below ground litter pools. In CLM4, the allocation of NPP to the plant pools is complex, as it considers the specified relationship among C allocation to new leaf, new stem as well as new fine and coarse roots (Thornton & Zimmermann, 2007). The C transfer among pools is sensitive to climate conditions. Unlike, CABLE and CLM-CASA, this model does not have representation of respiration from CWD. The turnover time for CLM4 ranges from several days to decades for different pools.

### Model Simulations and Diagnosis

The C dynamics in models heavily depends on the initial conditions of state variables. In this study, the steady state of models was achieved through spin up simulations in order to estimate the C variables. The models were run until the mean changes in plant C pools over each cycle (1 year) were smaller than 0.01% per year compared to previous cycle. The climate data used in this study was obtained from Qian *et al.* (2006). The models were run on default resolutions of  $1^\circ \times 1^\circ$  (CLM4),  $2.81^\circ \times 2.81^\circ$  (CLM-CASA) and  $1^\circ \times 1^\circ$  (CABLE) which is in line with other model comparison studies (e.g. Friedlingstein *et al.*, 2006).

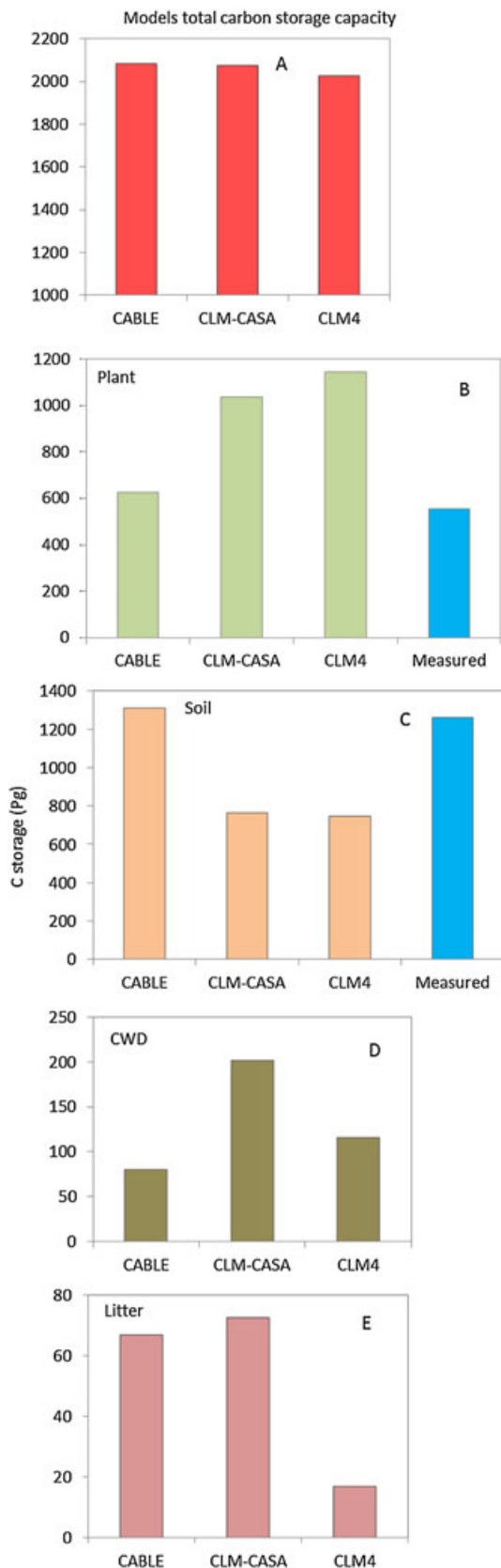


Figure 1. Comparison of C storage capacity among global land models: CABLE, CLM-CASA and CLM4. The results are reported as (A) Total, (B) plant, (C) soil, (D) coarse woody debris (CWD) and (E) litter C storage, respectively. Plant and soil C storage are also compared with available observed data (plant C taken from Gibbs, 2006; soil C taken from HWSD). Total modeled C storage is the sum of plant, soil, CWD and litter pools.

The data achieved from model spin ups were used to calculate average global values for the C variables, e.g. C storage, C residence time, NPP allocation and C transfer rates. To examine each model's structural differences, their total C storage capacity and residence time were decomposed into four pools: plant, CWD, litter and soils. To illustrate each model's behavior in finer scale, the plant, litter and soil pools were even further decomposed into their respective components. The plant pool was decomposed into leaf, stem and root C pools. The litter pool was decomposed in to structural and metabolic litter pools (different names are used in different model). The soil C pool was decomposed in to fast; slow and passive SOM pools. The C residence time in each pool was determined by the ratio of C pool size and C influx for the steady state. The C storage capacity of each model was compared with the plant data extracted from the database, GLC2000, described by Gibbs (2006), and soil C data obtained from the Harmonized World Soil Database (HWSD) (Todd-Brown *et al.*, 2013). Because of the unavailability of observed data for CWD and litter pools, the modeled results were compared among with each other. The C residence based on HWSD and MODIS NPP (Heinsch *et al.*,

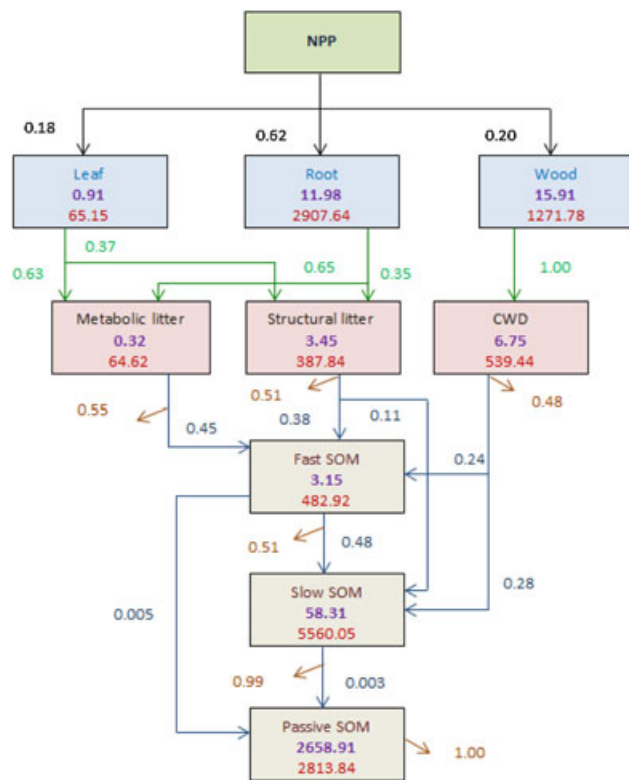


Figure 2. The C cycle scheme for the CSIRO Atmosphere Biosphere Land Exchange (CABLE) model. Black line and corresponding numbers show the partitioning coefficients of plant C pools. Green lines and corresponding numbers show the mortality fluxes of live tissues. Blue lines illustrate the flow of C among litter and soil C pools, while brown lines represent the respiration fluxes. Bold violet colored numbers in each pool are the C residence time (years), while the other red colored numbers in each pool represent the C storage capacity in unit of  $g\ C\ m^{-2}$ .

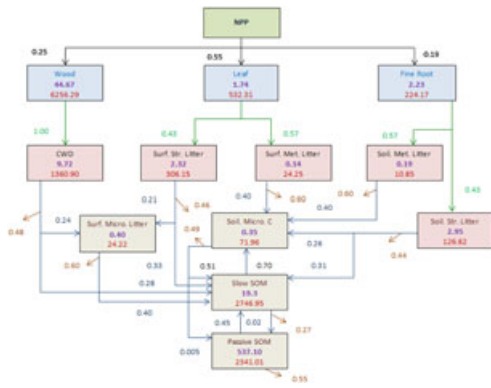


Figure 3. The C cycle scheme for the Community Land Model (CLM-CASA). Black lines and corresponding numbers show the partitioning coefficients in plant pools. Green lines and corresponding numbers show the mortality fluxes of live tissues. Blue lines illustrate the flow of C among litter and soil C pools, while the brown lines show the respiration fluxes. Bold violet colored numbers in each pool are the C residence time (years), while the other red colored numbers in each pool represent the C storage capacity in unit of  $g C m^{-2}$ .

2003) was also estimated to compare with modeled C residence times. To examine the models' fundamental differences in terms of number of C pools, partitioning and

transfer coefficients, a series of flow diagram were developed based after careful examination of computer codes of each model.

## RESULTS

### Carbon Storage Capacity

The total C storage capacity simulated by the three models was comparable among them (Figure 1A); however, we found substantial differences in the way they stored C in different pools. For example, CABLE stored more C in soil pool while the other two models stored most of the C in plant pools (Figure 1 B&C). The total amount of C stored in the plant pool of CABLE was comparable to the GLC2000 data. The plant pool of CLM-CASA and CLM4 showed 46% and 51% higher C storage capacity, respectively, compared to observed data. We observed a similar trend between simulated and the HWSO derived soil C storage data. The highest value of CWD (201.1 Pg C) was obtained from CLM-CASA followed by CLM4 (115.9 Pg C), then CABLE (79.7 Pg C) (Figure 1 D). The litter C storage capacity was the lowest in CLM4 (16.84 Pg C),

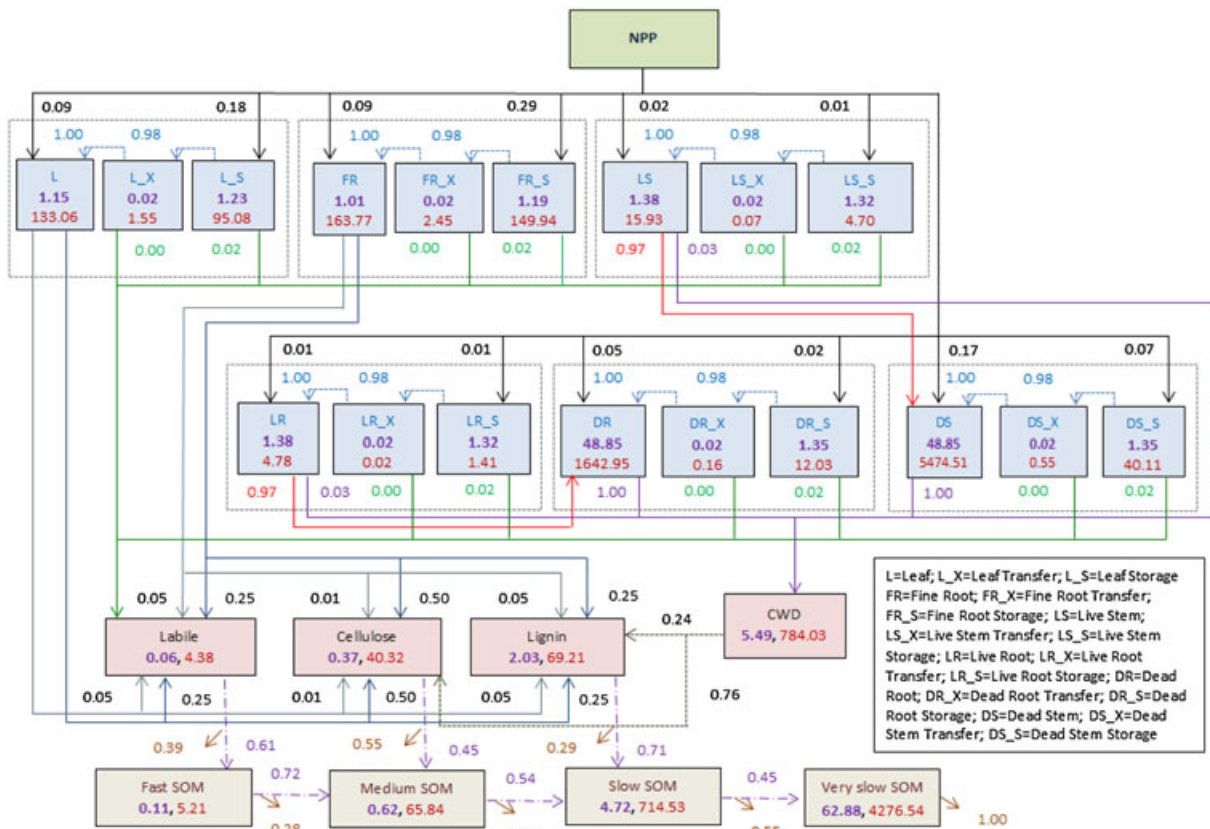


Figure 4. The C cycle scheme for the community land model version 4 (CLM4). Black lines and corresponding numbers show the partitioning coefficients in plant pools. The blue color lines and corresponding numbers within the dotted boxes are for the C transfer from storage to displayed C pools. Red lines and corresponding number represent turnover of live into dead tissues. Green lines and corresponding numbers show the mortality fluxes, except the leaf and fine root tissues. The blue line and corresponding number show the mortality fluxes from the leaf and fine root tissues. The dark gray lines and corresponding numbers show the additional shedding of live tissues under stress period. The violet lines show the mortality of woody tissues into coarse woody debris (CWD) pool. Dotted violet lines illustrate the flow of C among litter and soil C pools while the brown color lines show the respiration fluxes. Bold violet colored numbers in each pool are the C residence time (years), while the other red colored numbers in each pool represent the C storage capacity in unit of  $g C m^{-2}$ .



which was 76% and 74% lower than that of CLM-CASA and CABLE, respectively (Figure 1 E).

The individual values of C storage for all components in the CABLE model are presented in Figure 2. The plant pool stored more C in roots (429.8 PgC), which was 56% and 97% higher than C stored in wood and leaf, respectively. Among litter pools, the CWD showed the highest C storage compared to metabolic and structural litter pools. The slow SOM component of soil pool showed the highest C storage capacity (821.8 Pg), which was substantially higher than that of the fast SOM and passive SOM components.

The individual values of all C storage components in the CLM-CASA model are presented in Figure 3. The plant pool stored more C in woody tissue (stem part) (984.7 Pg), which was 96% and 91% higher than the C stored in roots and leaves, respectively. The slow SOM component of the soil pool displayed the highest C storage (405.9 Pg), which was 97% and 14% higher than the soil microbial and passive C components, respectively.

The CLM4 model showed a more sophisticated C storage dynamics among its different pools (because of additional short-term and long-term C storages), as compared to CABLE and CLM-CASA. The maximum C storage was in the dead stem and root tissues according to CLM4. The CWD among litter pools displayed the highest storage (115.9 Pg) which was 99%, 94% and 91% more than that of the labile, cellulose and lignin components, respectively. Similarly, the very slow soil C

component (632.1 Pg) was 99%, 98% and 83% larger than the C storage of fast, medium and slow C components, respectively (Figure 4).

*Carbon Residence Time*

The C residence time in root, litter and soil pools was longer in CABLE as compared with the other two models. For CLM4 the C residence time in leaf and woody tissues was the longest (Figure 5), when compared to the respective components in other two models. The C residence time for CWD component in CLM-CASA was much longer than that of CLM4 and CABLE. The modeled C residence times for the plant and soil pools by CABLE were in close agreement with the estimated C residence time (derived from HWS and MODIS NPP) (Figure 6). The C residence time of 35.8 years simulated by CABLE was the longest with a minimum NPP of 58.2 Pg year<sup>-1</sup>. The C residence time and NPP were negatively correlated.

The residence time of the individual C pools for CABLE are presented in the Figure 2. The CABLE model simulated longest C residence time of 15.9 years for woody tissue component of the plant pool. In the soil pool of CABLE, the passive component exhibited a C residence time of 2658.5 years, considerably longer than the other components of soil C pools. The individual values of C residence time of all components in CLM-CASA are presented in Figure 3. The longest C residence time of 44.7 years was for the woody tissue component. Likewise, the passive soil C component showed a residence time of 537.1 years

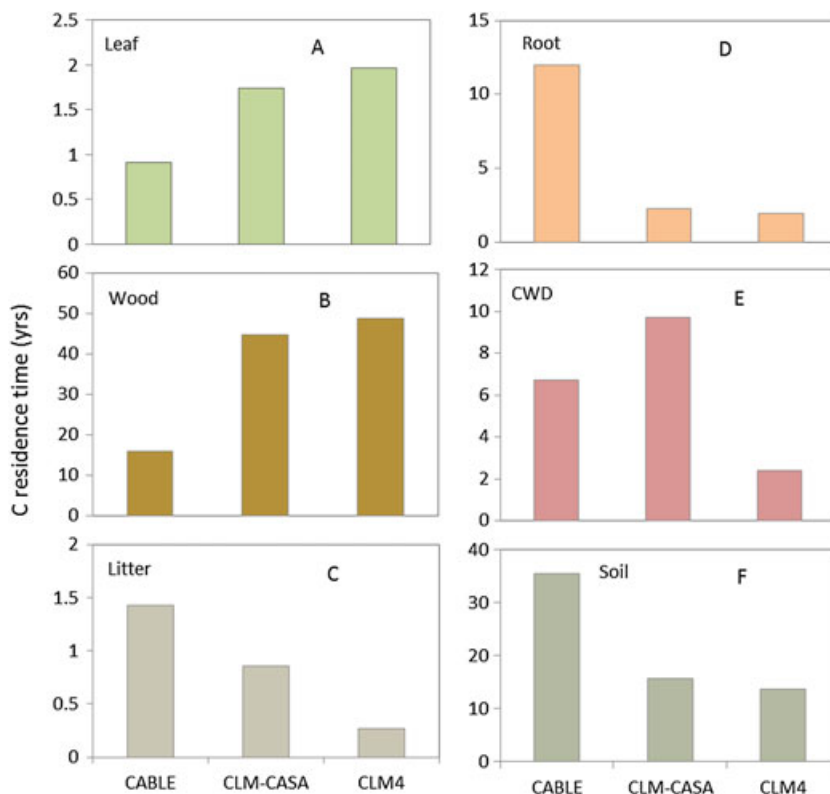


Figure 5. The C residence time among global land models: CABLE, CLM-CASA and CLM4. The results are aggregated from individual C pools to (A) leaf, (B) wood, (C) litter, (D) root, (E) coarse woody debris (CWD) and (F) soil C pools, respectively.

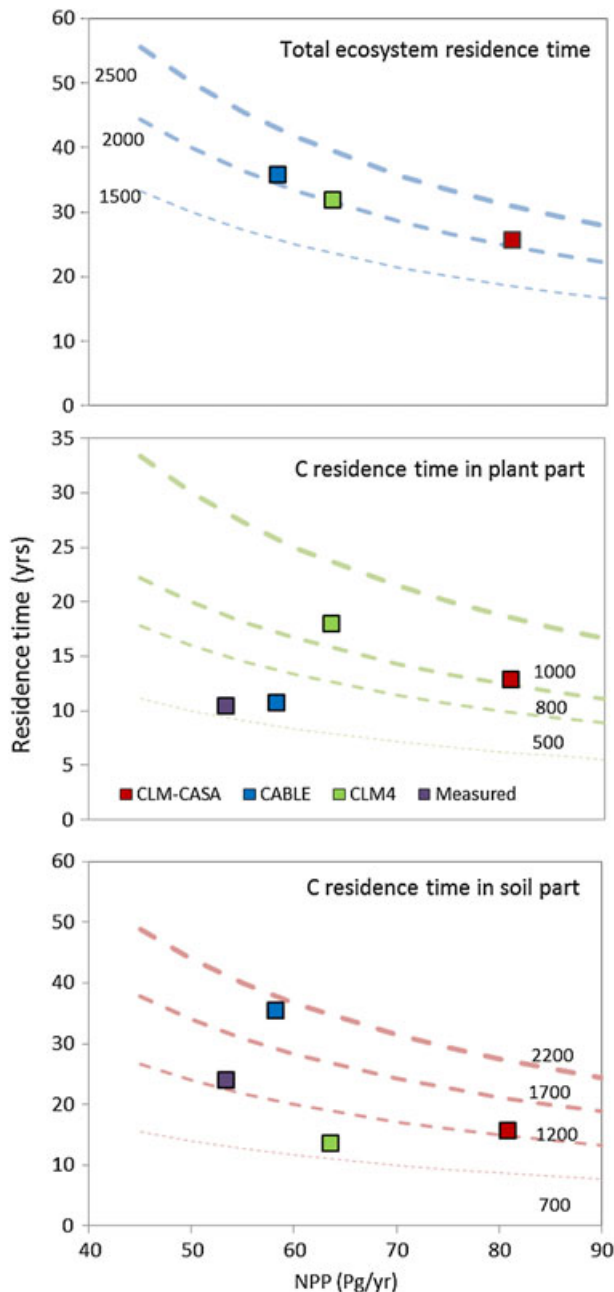


Figure 6. The C residence time in relation to net primary productivity (NPP), simulated by three global land models: CABLE, CLM-CASA and CLM4. (A) is the total ecosystem residence in relation to total NPP, (B) is the total C residence time of plant part (vegetation) in relation to total NPP and (C) is the total C residence time of soil in relation to total NPP. Contour lines represent the C storage capacity for given NPP and C residence times.

which was much longer than other soil C components. The individual values of C residence time of all components in CLM4 are presented in Figure 4. Compared to CABLE and CLM-CASA, the CLM4 model simulated a much shorter C residence time especially for soil C components. A maximum C residence time of 48.9 years was estimated for both the dead stem and dead coarse root components of the plant pools. With the exception of the woody C component, the other plant pools did not show a residence time of longer

than 2 years in this model. Similarly, among the soil C pool components of CLM4, very slow C component showed the longest C residence time of 62.9 years (Figure 4).

#### Models Structure, NPP Allocation and Carbon Transfer Coefficients

The global average NPP of  $81.9 \text{ Pg C year}^{-1}$  simulated by CLM-CASA was 28% and 21% higher than the NPP simulated by CABLE and CLM4, respectively. CABLE allocated 62% of NPP to root tissue, 20% to wood and 18% to leaf components of plant pool (Figure 2). Likewise, CLM-CASA allocated 55% of NPP to leaf, 25% to wood and 20% to root components (Figure 3). CLM4 displayed a completely different NPP allocation pattern (Figure 4) by allocating 38% and 27% of NPP to the fine root and leaf tissues, respectively. There was no direct NPP allocation to the short-term storage pool which only served as a C transfer mechanism from long-term storage to the displayed vegetation C pool.

The transfer of C from plant tissues to litter and soil pools was significantly different among the three models. In CABLE, the live tissues dispersed into three litter components (including CWD), after mortality. Leaves distributed 63% and 37% of their C to metabolic and structural litter components, respectively, while roots distributed 65% and 35% of their C to these components (Figure 2). In CLM-CASA, the live tissue components were dispersed into six different litter components (including CWD), after mortality. The leaves distributed 57% of C to surface metabolic litter and 43% to surface structural litter. Likewise, the fine roots dispensed 57% of C to soil metabolic litter and 43% to soil structural litter. All of the litter components contributed to three soil C pool components which were interlinked for back and forth movement of C until it was completely respired (Figure 3).

The litter fall scheme in CLM4 was entirely different than that of CABLE and CLM-CASA. The plant pools storage and transfer components collectively produced natural mortality fluxes at a constant rate of 2%. In addition, the leaf and fine root tissues also produced litter fluxes during offset periods (Figure 4). After reaching their maturity stage, 97% of live stems and live coarse roots were retained as a part of the dead woody structure. All of the litter pools end up in the soil C pools with a significant loss through respiration. As the soil C moved from the fast to the very slow component, the C transfer rate decreased progressively. Overall, CLM-CASA presented a more advanced definition of litter pools, while CLM4 displayed highly sophisticated litter fall schemes and CABLE showed the simplest structure for litter components distribution and litter fall pattern.

#### Spatial Pattern of NPP, Carbon Storage and Residence Time

The global spatial distribution of NPP, C storage capacity and C residence widely differed among the three models, despite their comparable total C storage capacities. In general, CLM-CASA produced much higher NPP in tropical regions compared to CLM4 and CABLE, respectively (Figure 7).

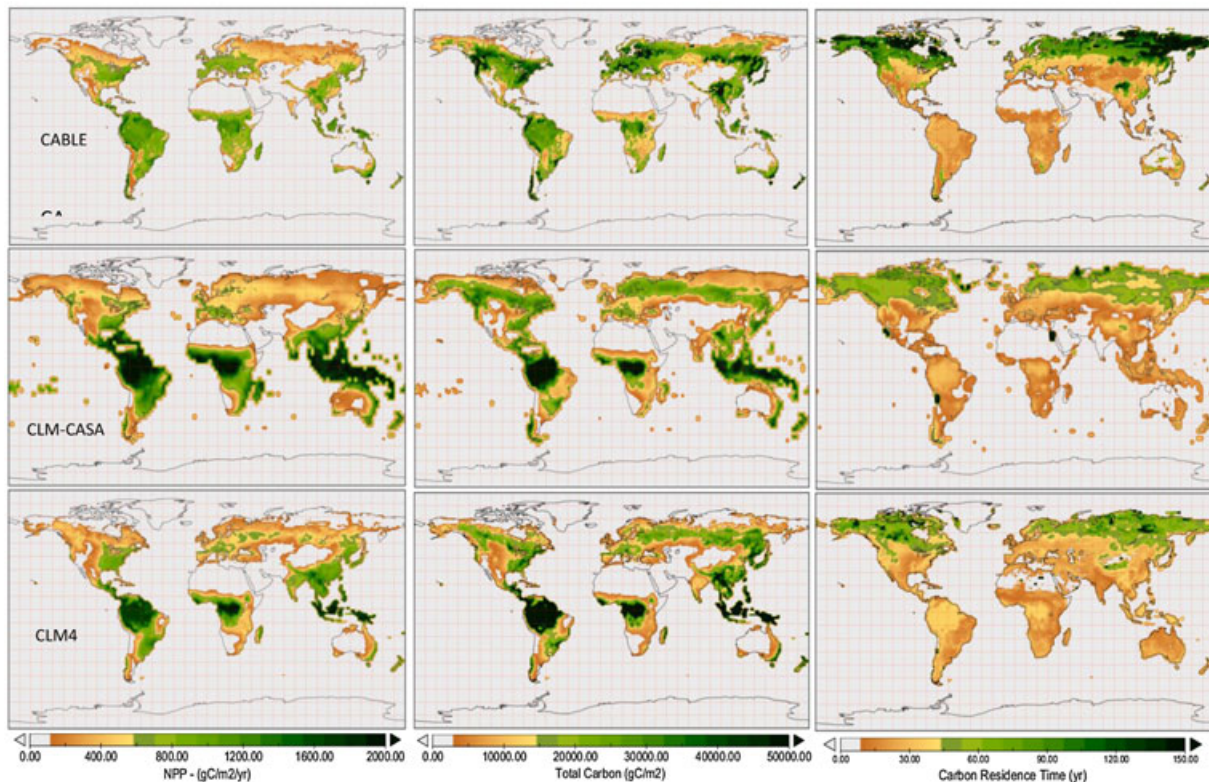


Figure 7. Spatial distribution of simulated net primary productivity (NPP), total ecosystem C storage and C residence time in global land models: CABLE, CLM-CASA and CLM4.

Similarly, the C storage in boreal and temperate regions for CABLE was higher than simulated by CLM-CASA and CLM4. Furthermore, all of the models reflected the highest C residence time in boreal regions, compared to other parts of the globe. This trend was much higher in CABLE than other two models. For example, the average C residence time of >150 years for boreal regions in CABLE was much higher than the C residence time of >50 years in CLM-CASA.

## DISCUSSION

Accurate estimation of terrestrial C storage is critical for the better understanding of climate-C feedback. In this study, we assessed C storage capacity and C residence times in three commonly used land models: CABLE, CLM-CASA and CLM4. Results showed that there was not a significant difference in the total global C storage capacity simulated by three models. However, notable differences were observed in C storages for different C pools (plant, soil, litter) among three models. CABLE stored more C in soil pools, while, CLM-CASA and CLM4 stored more C in the plant pools. Much of the difference in soil C in CABLE was driven by the passive soil C component (2659 years compared to 63 and 537 years in CLM4 and CLM-CASA). Overall, the net effect was a relatively fast turnover of the entire C pool in CLM-CASA (26 years), a moderate turnover time for CLM4 (32 years), and a relatively slow turnover time for CABLE (36 years). These results are

consistent with Zhang *et al.* (2010), Bonan *et al.* (2013) and Xia *et al.* (2013).

NPP allocation to different plant pools plays a critical role in the C storage (Zhou & Luo, 2008; Köchy *et al.*, 2015a). In this study, CABLE allocated major portion of NPP to roots, whereas, CLM-CASA and CLM4 allocated to leaves and fine roots, respectively. In CABLE, the largest portion of NPP allocated to the roots, resulted in higher C storage and longer C residence time in the soil. This pattern of higher C storage under higher NPP allocation is in agreement with other studies (Wang *et al.*, 2011a, 2011b; Todd-Brown *et al.*, 2013). This indicates the fact of improving NPP projections in models (Köchy *et al.*, 2015b). Similarly, the variations in C storage and residence times can also be largely influenced by the C transfer rates among the C pools (White & Luo, 2002; Weng *et al.*, 2011). CABLE transferred about 36% of C from leaves and roots to structural litter pool as compared to 43% in CLM-CASA. This difference in C transfer rates substantially affected the C storage and C residence times in three models. Overall, for the entire C cycle, CLM4 respired relatively less C and transferred more C among the pools as compared to CABLE and CLM-CASA.

Even though, NPP allocation and C transfer rates are the major contributors in regulating C storages in models, the models' structural differences cannot be overlooked. Models' structural differences can also offer some possible explanation for the variations in C storage capacity and C residence times among models. CABLE, CLM-CASA



and CLM4 differed significantly in terms of number and diversity of C pools and their components, ranging from 9 C pools in CABLE, to 12 in CLM-CASA and 26 in CLM4. Based on the structural pattern and nature of the C pool linkages, we can characterize CABLE, CLM-CASA and CLM4 as simple, moderately complex and complex models, respectively. For example, CLM-CASA presented a more advanced definition of litter pools with a clear distinction between surface and soil litters. Likewise, CLM4 showed highly sophisticated and advanced schemes of multiple litter fall fluxes during different times of the year. In contrast, CABLE showed a straightforward and a more simple litter fall distribution scheme. The prevailing view among experts is that larger numbers of C pools better represent complexity of ecosystems and their spatial variations (Todd-Brown *et al.*, 2013). However, this was not evident in our study. We observed that the structural features were clearly related to the models' results and their agreement with reference data, with respect to the number of C pools. In terms of C storage capacity in plant and soil components, CABLE (a relatively simple model) showed better agreement with reference data. These results call for further examination of the benefits to be gained from increased complexity of models, beyond process understanding.

The analysis presented in this study was based on the natural state of C pools in models. However, human disturbance of the land surface through land managements (Fialho & Zinn, 2014; Parras-Alcántara & Lozano-García, 2014; Rafique *et al.*, 2014; Srinivasarao *et al.*, 2014; Tsibart *et al.*, 2014; de Moraes Sá *et al.*, 2015; Kaleem *et al.*, 2015; Novara *et al.*, 2015) was not considered in this study. For example, C transfer rates among C pools are largely influenced by the decomposition rates, which in turn depend on the direct effect of land use (Rafique *et al.*, 2013; Kumar *et al.*, 2013; Fialho & Zinn, 2014; Musinguzi *et al.*, 2015), land degradation (Yu & Jia, 2014; Peng *et al.*, 2015) and fires (Tsibart *et al.*, 2014). What is more, the effects of permafrost on C cycling should also be considered (Zubrzycki *et al.*, 2014; Ping *et al.*, 2015). As a step forward, this study can be further improved by incorporating the effect of these factors over time. Nevertheless, this study has wider implications and is helpful in revealing the underlying differences among models which is a fundamental step in explaining the models' behaviors. This study also provides information on the importance of different components and possible source of variations which can be useful for further model improvement, model intercomparison and data assimilation.

### CONCLUSION

Three widely used land surface models (CABLE, CLM-CASA and CLM4) were driven with the same meteorological forcing and their global C simulations were used for inter-comparison and structural analysis with a focus on the C storage and residence time of different C pools (plant,

litter and soil). CABLE was found to give better representation in simulating global carbon estimation. CABLE stored more C in the root tissues, whereas, CLM-CASA and CLM4 stored more C in the woody tissues. CLM-CASA displayed a fast turnover time compared to CLM4 and CABLE, respectively. The CABLE model allocated more C to roots, CLM-CASA to leaves, and CLM4 to fine roots and leaves. This allocation pattern resulted in more recalcitrant C in CABLE. Substantial differences were also observed in the transfer of C among pools and corresponding respirational fluxes in three models. These differences affected the respective C pools size and residence times. CLM4 respired less C and transferred more C among its pools and components in comparison to other two models. By diagnosing and detangling the different behaviors from the perspective of model structures, our results provide useful guidance for the further model development and parameterization. Moreover, the diagnosing framework can be well extended to other aspects of C dynamics of interest (e.g. photosynthesis) in order to identifying and narrowing down the uncertainties in their future predictions.

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