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# Structural analysis of three global land models on carbon cycle simulations using a traceability framework

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## Abstract

Modeled carbon (C) storage capacity is largely determined by the C residence time and net primary productivity (NPP). Extensive research has been done on NPP dynamics but the residence time and their relationships with C storage are much less studied. In this study, we implemented a traceability analysis to understand the modeled C storage and residence time in three land surface models: CSIRO's Atmosphere Biosphere Land Exchange (CABLE) with 9 C pools, Community Land Model (version 3.5) combined with Carnegie-Ames-Stanford Approach (CLM3.5-CASA) with 12 C pools and Community Land Model (version 4) (CLM4) with 26 C pools. The globally averaged C storage and residence time was computed at both individual pool and total ecosystem levels. The spatial distribution of total ecosystem C storage and residence time differ greatly among the three models. The CABLE model showed a closer agreement with measured C storage and residence time in plant and soil pools than CLM3.5-CASA and CLM4. However, CLM3.5-CASA and CLM4 were close to each other in modeled C storage but not with measured data. CABLE stores more C in root whereas CLM3.5-CASA and CLM4 store more C in woody pools, partly due to differential NPP allocation in respective pools. The C residence time in individual C pools is greatly different among models, largely because of different transfer coefficient values among pools. CABLE had higher bulk residence time for soil C pools than the other two models. Overall, the traceability analysis used in this study can help fully characterizes the behavior of complex land models.

## 1 Introduction

Atmospheric CO<sub>2</sub> is a major driver that controls the climate (Canadell et al., 2007). Strong evidence shows that the terrestrial ecosystem has been acting as a net C sink over the past few decades (Lund et al., 2010). However, it is unclear if this sink will persist in future climate conditions. The C storage in terrestrial ecosystem is immensely

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several ensemble studies (Johns et al., 2011; Roeckner et al., 2011), which have significantly enhanced the understanding of models behavior but still lack the adequate information in attributing the sources of uncertainties.

The increasingly complex global land models have become an integral tool for understanding the C cycle as well as analyzing various other hypotheses at different temporal and spatial scales. These models, based on several assumptions and formulations of processes, control the C dynamics in various ways. Thus, there is great diversity in the complexity of the model structures and their simulated C results. For example, the Coupled Model Intercomparison Project (CMIP4) reported that the C uptake varied from 100 to 800 Gt C in response to doubled CO<sub>2</sub> concentration amongst 11 climate models over a period of 1850–2100 years (Friedlingstein et al., 2006; Arora et al., 2011). Models are conventionally analyzed by comparing outputs among different models as well as with referenced data sets, (Wang et al., 2011a, b) which are not enough to understand the underlying behavior of the models. For example, Mishra et al. (2013) have identified the modeling uncertainties of soil C in permafrost regions but insufficiently attributed these variations to their sources. This shortcoming can only be addressed after gaining a thorough understanding of the model's fundamental structural differences and understanding its traceable components controlling the C dynamics.

It is uncertain as to whether the discrepancies amongst the models arise from differences in photosynthetic C influx, model structure (including number of C pools, their connecting structure, and the parameter's environmental dependencies) and/or model parameterization (including transfer coefficients and parameterization of environmental dependencies) (Luo et al., 2001). Previous research has shown that the diversity between soil C stocks and C pool within models can be explained by the differences between NPP simulation, decomposition rate and temperature sensitivity (Todd-Brown et al., 2013, 2014). However, this work did not disentangle the effects of the pool structure or parameterization regarding bulk decomposition rate and temperature sensitivity. To accomplish this, analyses such as the aforementioned, would need to be performed on each land model.

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To obtain robust estimates of C dynamics for the accurate prediction of future climate, we must first focus on the model's structural analysis as well as characterize the complexity of C cycle in the models. Therefore, we conducted a traceability analysis in three commonly used land models (CABLE, CLM3.5-CASA and CLM4) to examine the C storage and the residence time. The traceability analysis decomposes the land model into traceable components based on mutual independent properties of biogeochemical processes. This framework defines ecosystem C storage capacity as a product of NPP and ecosystem residence time. The latter plays an important role and is determined by the NPP allocation and C transfer coefficients among pools. In this study, we first evaluated the models performance against the measured global C storage and residence time. Secondly, we decomposed the complex models into traceable components of C storage and residence time in order to examine the underlying differences in the model structures. Thirdly, we estimated the C partitioning and transfer coefficients as well as their potential contribution in determining the C storage and residence time.

## 2 Methods

Basic understanding of the fundamental structures and properties of land models is necessary for rigorous model analysis. All of the models simulate four common properties of C cycling: (1) photosynthesis as the common starting point of C flow in an ecosystem, (2) partitioning of assimilated C into different vegetation compartments, (3) C transfer is controlled by donor pool, and, (4) first order decay of litter and soil organic matter (SOM). Mathematically, these basic properties can be expressed as:

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

where  $X(t)$  is a vector representing the C pool sizes,  $\mathbf{A}$  is the C transfer matrix,  $U$  is C input via photosynthesis,  $B$  is partitioning coefficients from the inputs to various C

pools and  $X(0)$  is the initial value of the C pool. The  $\mathbf{A}$  matrix is conditioned by environmental scalar (temperature and water) values (Luo et al., 2012). In these equations, long term ecosystem C storage is the product of C inputs multiplied by residence time (Luo et al., 2003). The parameters of  $X(t)$ ,  $\mathbf{A}$ ,  $B$  and  $U$  enable us to apply the mass balance approaches and decompose the models into traceable components. The general description of the models used in this study is given below.

## 2.1 CABLE

CABLE is an Australian CSIRO's Atmosphere Biosphere Land Exchange (CABLE) model use to simulate land atmospheric exchanges (Kowalczyk et al., 2006). CABLE is a key component of the Australian Community Climate Earth System Simulator (ACCESS) and consists of five modules: (1) radiation module to compute absorption and transmission of light, (2) canopy micrometeorology describes the canopy features based on the theory developed by Raupach (Raupach, 1994), (3) soil module describes the heat and water fluxes, (4) surface flux module derives the energy balance, transpiration, stomata conductance and photosynthesis, (5) ecosystem C module estimates the respirational losses. The ecosystem C module, also known as the biogeochemical cycle sub-model, evolved from CASACNP, a model developed by Wang (Wang et al., 2010). CASACNP contains the coupled C, nitrogen (N) and phosphorus (P) cycles. There are nine C pools in the CABLE model; three plant pools (leaf, root, wood), three litter pools (metabolic, structural and CWD), and three soil pools (microbial biomass, slow and passive SOM). Ecosystem C influx (i.e., NPP) is the difference between gross primary productivity (GPP) and autotrophic respiration. The seasonal growth and decay of biomass is determined by partitioning of NPP into leaves, roots and wood. The C partitioning coefficients of photosynthetically fixed C into plant pools are determined by the availability of light, water and N. The flow of C from vegetation to soil pools is characterized by a simple C pool model described in (Dickinson et al., 1998). The equations that explain changes in pool size over time have been explained in (Wang et al., 2010). The leaf and root mortality ends up in metabolic and structural litter pools,

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whereas, woody tissues go to coarse woody debris (CWD) pool. The C transfer coefficients are determined by the lignin/nitrogen ratio from plant to litter pools and the lignin fraction from litter to soil pools. The potential decay rates of different C pools are first preset and vary with vegetation types, lignin fraction and soil texture. The environmental scalar regulates the leaf turnover rates via limitations of soil moisture and soil temperature conditions. The more detailed description of CABLE model is given in Wang et al. (2011a) and Xia et al. (2013).

### 2.2 CLM3.5-CASA'

CLM3.5-CASA' model combines the biogeophysics of the CLM3.5 with Carnegie-Ames-Stanford Approach (CASA) biogeochemistry module. The CLM3.5 (Community Land Model-version 3.5) released in 2008, is a component of the Community Earth System Model (CESM) of the National Center for Atmospheric Research (NCAR). CLM3.5 is used for a variety of climate change simulations at different temporal and spatial scales (Doney et al., 2006). CLM3.5 examines the physical, chemical, and biological processes through which terrestrial ecosystems interact with climate (Oleson et al., 2008). Along with the integration of CASA' into the CLM3 (an earlier version) model, several changes also made in CLM3.5 specifically relating to model hydrology, canopy integration, canopy interception scaling and plant functional types (PFT). The land surface is divided into five sub-grid land cover types (glacier, lake, wetland, urban, vegetated). The vegetated part is further divided into sixteen plant functional types (PFTs) which compete for water and nutrients on a single soil column. The land atmospheric exchanges are defined at the PFT level in CLM3.5.

CASA' simulates PFTs beginning with C assimilation via photosynthesis, to mortality and decomposition, and finally the release of CO<sub>2</sub> to the atmosphere through respiratory losses. There are 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). The rates of C transfer among the pools are sensitive to climate variations. In CASA', NPP is

the 50% quotient of GPP which is allocated to the three plant C pools with preferred allocation to roots in water-limited and to leaves in light-limited situations (Friedlingstein et al., 1999). The leaf mortality ends up in metabolic and structure surface litter, whereas, root mortality culminate to metabolic and structure soil litter and wood mortality to CWD. The subsequent decomposition of litter pools leads to the transfer of C to the dead surface, soil microbial and the slow and passive SOM pools. The turnover time ranges from several months to hundreds of years. A fraction of each C transfer is returned to the atmosphere through heterotrophic respirational processes. A more detailed description of the model is provided by Doney et al. (2006).

## 2.3 CLM4

The CLM4 is an upgraded version of CLM3.5 (Gent et al., 2011), and is being used as land component in CESM1.0. This model has more advanced global map of PFT, wetland and lake distributions and accurate optical properties of grassland and cropland areas. The CLM4 also represents a significant enhancement in model structure and model parameterizations. Among the most significant changes is addition of C and N cycle based on the terrestrial biogeochemistry Biome-BGC model (Thornton and Rosenbloom, 2005; Thornton et al., 2009). It is prognostic with respect to C and N state variables in vegetation, litter and SOM. These state variables are tracked for leaf, live stem, dead stem, live coarse root, dead coarse root, and fine root pools. Each of these pools has two corresponding C storage pools for short and long term storage.

The CLM4's discrete phenology types are represented by separate algorithms: evergreen, seasonal deciduous and stress-deciduous (Lawrence et al., 2012). In evergreen phenology, litterfall is specified to occur through background mechanism which is continuous shedding of foliage and fine roots. The seasonal deciduous phenology algorithm is based on the parameterizations for leaf onset and offset periods (Lawrence et al., 2011), where, litterfall occurs only when day length is shorter than a certain value. The stress deciduous phenology algorithm is based on grass phenology pattern (White et al., 1997) and exhibits multiple growing seasons.

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The CLM4 also simulates both autotrophic and heterotrophic respirations. Autotrophic respiration (AR) is equivalent to the sum of maintenance respiration (MR) and growth respirations (GR). Maintenance respiration is calculated as a function of temperature and N concentration of live tissues (Thornton and Rosenbloom, 2005), whereas GR is calculated as a constant factor (0.3 times) of the C allocated to growth. The daily MR rate is set as 218gC respired per g of N at 20°C temperature. For heterotrophic respiration (HR), a converging cascade of C dynamics is simulated with three litters (labile, cellulose, and lignin), CWD and four SOM pools (fast, medium, slow, and very slow). There is no distinction between surface and belowground litter pools. The litter pools are defined on the basis of commonly measured chemical fraction of fresh litter. The litter and SOM pools differ in decomposition rates, with a turnover time ranging from hours to years (Thornton and Rosenbloom, 2005). Decomposition rates are function of soil temperature (Lloyd and Taylor, 1994) and soil water potential (Olof and Paustian, 1987). There is no respiration flux from CWD pool.

### 2.4 Models simulations

The steady state of the models was obtained through spin up simulations for many years. Briefly, the models first read in all meteorological input values and initial C pool sizes and then continuously run with recycled meteorological forcing variables for hundreds of years until steady state is achieved. This process was accelerated for the CABLE and CLM3.5-CASA models, which were run to steady state using the semi analytical solution (SAS) method developed by Xia et al. (2012). The SAS method is fundamentally based on the analytical solution of equations that describe C transfers within the ecosystem over time. SAS was implemented in three stages: (1) setting up an initial spin up with prior pool size values till the NPP becomes stable, (2) calculating quasi steady state pools sizes by keeping fluxes of the equations equal to zero, and (3) having a final spin up to meet the criterion of steady state. The detail of the SAS implementation procedure is described in Xia et al. (2012). The CLM4 was spun using the traditional spin up method (accelerated decomposition) of long term iterative

simulations to achieve the steady state of the variables (Thornton and Rosenbloom, 2005).

We ran the models until the mean changes in plant C pools over each loop (1 year) were smaller than 0.01 % per year compared to previous cycle. These simulations were customized to not account the effect of any disturbance effect. The CLM4 and CLM3.5-CASA simulations were driven by QIAN's atmospheric input data (Qian et al., 2006) while, the CABLE model was forced with climate forcing described in Wang et al. (2010). However, from both forcing data, the 1990 year was selected as the baseline to compare models output. The models were run on three different latitude and longitude resolutions  $0.9^\circ \times 1.25^\circ$  (CLM4),  $2.81^\circ \times 2.81^\circ$  (CLM3.5-CASA) and  $1^\circ \times 1^\circ$  (CABLE) (Table 1). The CLM4 simulations were conducted at the NCAR's Yellowstone computing system while CABLE and CLM3.5-CASA were run locally in the Super Computing Center for Education and Research (OSCER) at Oklahoma University. Once the models were spun up to steady state, the data was stored for calculations of C storage, C residence time, and C partitioning and transfer coefficients.

## 2.5 Diagnosis

The diagnosis explains the hierarchy of the models and demonstrates how the model outputs were used to examine the behavior of the simulated C storage and residence time. The majority of land modeling studies addresses the differences between measured and modeled data. However, they rarely explain the hidden discrepancies amongst the model structures, such as what fraction of C is transferred amongst the pools or how much biomass accumulates in the different pools? In attempt to address this issue, the C model structure was dissected and a thorough examination was performed. Several steps were followed to estimate each model's C storage capacity, residence time, partitioning coefficients and transfer coefficients. The stored data from model spin ups were used to calculate average global values for the C variables in the models. Total ecosystem C storage capacity is the sum of C in all pools. The C residence time in each pool was determined by the ratio of C pool size and C influx

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in a steady state. The C storage capacity of each model was compared with the plant data extracted from the database described by Gibbs (Gibbs, 2006), and soil C data obtained from the Harmonized World Soil Database (HWSD) (Todd-Brown et al., 2013). Global spatial maps were also created to examine the regional distribution patterns of NPP, C storage and residence time of the models.

The observed C residence time (plant and soil C) was also compared with the modeled results. To estimate the observed C residence time using HWSD, we obtained MODIS (MOD17A3) annual NPP of the year 2000 organized by US National Aeronautics and Space Administration (NASA) Earth observing Systems (EOS) (Heinsch, 2003). To elaborate the models fundamental differences in terms of number of C pools, partitioning and transfer coefficients, flow diagram were developed after carefully reading the computer codes. The linkages between the C pools and fluxes were organized into the C transfer matrix and partitioning coefficients vectors. NPP partitioning in different plant tissues was estimated based on the preset values of the models.

### 3 Results

#### 3.1 Carbon storage capacity

The global spatial distribution of C storage capacity and NPP among all three models widely differed. In general, all models displayed a larger amount of NPP in tropical areas followed by temperate and boreal regions (Fig. 1). However, CLM4 produces slightly more NPP in temperate regions compared to other two models. Similarly, CABLE reflected a larger amount of C storage in boreal and temperate regions compared to CLM3.5-CASA and CLM4. The majority of the boreal regions in CLM3.5-CASA and CLM4 displayed  $\sim 15000 \text{ g C m}^{-2}$  of C storage compared to  $\sim 25000 \text{ g C m}^{-2}$  in CABLE. Although these models displayed vast spatial variations, their total C storage capacity was not largely different (Fig. 2a).

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To examine each model's structural differences, their total C storage capacity was decomposed into four components: plant, CWD, litter and soils. We observed a compensatory behavior amongst the models, where CABLE prefers to store more C in one component while the other models favor other components (Fig. 2). In order to evaluate each model's performance, the total C storage in the plant and soil components was compared with the measured data (Fig. 2b and c). The total amount of C stored in the plant component of CABLE was found to be much closer to that of the amount reflected in the observed data. On the contrary, in comparison to the measured data, the plant component of CLM3.5-CASA and CLM4 showed a 46 % and 51 % larger C storage capacity, respectively (Fig. 2b). Likewise, the measured soil C storage followed the same trend, displaying results similar to those in CABLE; compared to CLM3.5-CASA and CLM4 (Fig. 2c). Due to the unavailability of measured data for CWD and litter pools, the modeled results were compared amongst each other. The highest C storage of CWD was displayed in CLM3.5-CASA with 201.14 Pg C followed by CLM4 and CABLE, respectively (Fig. 2d). The litter component displayed the lowest C storage capacity in CLM4; decreasingly 76 % and 74 % lower than that of CLM3.5-CASA and CABLE (Fig. 2e).

To illustrate each model's behavior in finer scale, the plant, CWD, litter and soil components were even further decomposed into each's respective sub-components. The root tissue of the plant component in CABLE displayed the largest C storage capacity, increasingly 56 % and 97 % more than C stored in wood and leaf, respectively. The CWD amongst litter pools showed the highest C storage; 88 % and 28 % higher than that of the metabolic and structural litter pools, respectively. Similarly, the slow SOM pool contains a larger C storage capacity than that of the fast SOM and passive SOM pools. The individual pools sizes of the CABLE model are shown in Fig. 3. The plant component in CLM3.5-CASA stored the majority of C in woody tissues (stem part), which was 96 % and 91 % higher than the C stored in root and leaf, respectively. The slow SOM pool of the soil component displayed the highest C storage, which was 97 % and 14 % higher than that of the soil microbial and passive C pool, respectively. The

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C influx is largely influenced by the basic differences in models structures. CABLE showed 9 different C pools compared to 12 in CLM3.5-CASA and 26 in CLM4. Each model's preferences were observed in terms of NPP allocation to different plant tissues. CABLE allocates 62 % of NPP to root tissue, 20 % to wood and 18 % to leaf (Fig. 3). Likewise, CLM3.5-CASA allocates 55 % of NPP to leaf, 25 % to wood and 20 % to root (Fig. 4). However, CLM4 displayed a completely different NPP allocation pattern; where C was allocated to the displayed and long term storage pools of leaf, live stem, dead stem, live coarse root, dead coarse root and fine root (Fig. 5). CLM4 allocates 38 % and 27 % of NPP to the fine root and leaf pools, respectively. There was no direct NPP allocation to the short term storage pool; it was observed that it only served as a passage for C transfer from long term storage to the displayed vegetation C pool. Depending on the algorithm implemented, the stored C is displayed as a new growth when required. The vegetation pool sizes are determined by the equilibrium of new growth, litterfall, mortality as well as other losses. The turnover of live stem and live coarse root to dead stem and dead coarse root is also a unique phenomenon in CLM4.

A large difference in the transfer of C from plant tissues to litter and soil pools was observed. In CABLE, the live tissues dispersed into three litter pools (including CWD) after mortality. Leaves distributed 63 % and 37 % C to metabolic and structural litter pools while, roots distributed 65 % and 35 %, respectively. The woody component directly progressed to the CWD pool, where it then divided into fast SOM and slow SOM pool. A major portion of litter C is released into the atmosphere through respiration losses, while the remaining is distributed into the fast and slow SOM pools. In CLM3.5-CASA, the live tissues dispersed to 6 different litter pools (including CWD) after mortality. The leaves distributed 57 % of its C to surface metabolic litter and 43 % to surface structural litter. Likewise, the fine roots dispensed 57 % of its C to soil metabolic litter and 43 % to soil structural litter. The woody tissues progressed directly to CWD which then contributes 24 % C to surface microbial litter and 28 % to slow SOM pool. All of the litter pools contribute to three soil C pools which are then interlinked for back and forth movement of C till it is get respired completely (Fig. 4).



showed larger accumulates in the plant pools. The litter, root and soil C pools display a longer residence time in CABLE (1.43, 11.98 and 35.47 years, respectively) compared to CWD in CLM3.5-CASA (9.72 years) and leaves and wood in CLM4 (1.96 and 48.86 years respectively). Overall, the net effect leads to a relatively fast turnover of the entire C pool in CLM3.5-CASA (25.65 years), a moderate turnover time for CLM4 (31.87 years) and a relatively slow turnover time for CABLE (35.77 years). Much of the difference in soil C in CABLE was driven by the passive SOC pool (2658.81 years compared to 62.88 and 537.10 years in CLM4 and CLM3.5-CASA). These results are comparable to those of other studies (Zhang et al., 2010; Bonan et al., 2013; Xia et al., 2013).

NPP allocation to C pools plays a critical role in the C cycle, thus the NPP allocation coefficients were carefully examined in order to determine how the C uptake is distributed among various pools (Zhou and Luo, 2008). The CABLE model allocated a major portion of the NPP to root tissues, whereas, the CLM3.5-CASA mainly favored leaf tissues. Similarly, the CLM4 allocated more NPP to fine roots and then leaf tissues. In CABLE, the large portion of NPP allocated to the root tissues, resulted in longer C storage and residence time in the soil component. This phenomenon differed from the occurrences of the other two models. These NPP allocation patterns cause fundamental differences of the C cycles in global land models also studied in other studies (Friedlingstein et al., 1999). This NPP allocation in the models was determined by the different assumptions of several simulated processes. In CABLE, the allocation of NPP into plant pools was determined by the availability of light, water and nitrogen (Xia et al., 2013), whereas, CLM3.5-CASA also considers the changes in atmospheric CO<sub>2</sub> concentration (Friedlingstein et al., 1999). In CLM4, the allocation of C to the plant pools was even more complex, as it considers the specified relationship among C allocation to new leaf, new stem as well as new fine and coarse root (Thornton and Zimmermann, 2007). According to Zhang et al. (2010), these variations can also be tracked back to the parameters of photosynthesis models, which are further determined by other environmental factors.

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NPP is one of the most influential drivers controlling the C dynamics in land models (Todd-Brown et al., 2013). The simulated NPP in all three models was comparable to that of other previous studies (Friedlingstein et al., 1999; Thornton and Zimmermann, 2007; Wang et al., 2011b). However, the NPP is not highly variable among the models due to similar environmental conditions. As expected the resultant C storage was also very similar among the models.

The variations amongst these models can also be largely explained by examining the C transfer rates from one pool to the others. The C transfer rates are generally determined by the input from C donor pools (White and Luo, 2002; Weng et al., 2011) and thus directly determine the C pools sizes and C residence times. Our results demonstrated that CABLE, CLM3.5-CASA and CLM4 were vastly diverse in transferring C fluxes among pools and their corresponding respirational fluxes. The values of the C transfer coefficients were inversely related to the residence time of C pools (Figs. 3, 4, 5). The CABLE model transfers 36 % of C from the leaf and root to the structural litter pool compared to 43 % in CLM3.5-CASA. This difference substantially affected the respective C pool size and residence time. Similarly, CLM4 showed no respiration fluxes from CWD; compared to CABLE and CLM3.5-CASA where 48 % C released back to atmosphere as CO<sub>2</sub> fluxes. Overall, throughout the C cycle, CLM4 respired relatively less C and transferred more C amongst the pools compared to the other two models. This transfer of C amongst the pools is dependent upon the environmental scalars as argued by Xia's traceability framework (Xia et al., 2013). The environmental scalar can influence the C dynamics in two ways. Firstly, when air temperature or water availability is too low, an additional fraction of C is released to the litter pool. Secondly, decomposition rates of litter and soil organic C pools are modified by temperature and water scalar. The substrate quality also strongly influences the soil organic C decomposition process.

The models structure is another possible explanation of the variations in C storage capacity and C residence time among models. The model structures, in terms of number of C pools showed great diversity ranging from 9 C pools in CABLE, to 12 in

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CLM3.5-CASA and 26 in CLM4. Based on the structural pattern and nature of the C pool linkages, we can characterize CABLE, CLM3.5-CAS and CLM4 as simple, moderate and complex model, respectively. For example, CLM3.5-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 simpler litter fall distribution. It is generally considered that the more number of C pools are flexible and represent better spatial variations (Todd-Brown et al., 2012) but this idea was not supported in this study. We observed that the structural features were clearly related to the models results and measured data agreement, with respect to the number of C pools (Fig. 2). In terms of C storage capacity in plant and soil components, CABLE (simple model) showed better performance followed by CLM3.5-CASA and CLM4 respectively. These results call into questions the advisability of increasing model complexity.

There can be several reasons for the discrepancy between modeled and measured data. One of the important factors can be the differences in the formulation of basic land cover types and the assumed areas represented by individual vegetation types in models. Secondly, these variations can be explained by uncertainties in the observed data having occurred due to measurement errors. Additionally up scaling schemes can introduce uncertainty in both the measured and modeled data at leaf and ecosystem levels (Gu et al., 2002). Finally, the treatment of wetland as a non-vegetated zone in models also enhances the deviation of the observed and modeled data (Thornton and Zimmermann, 2007). This substantial disagreements between models and measured has also been observed in other studies (Friedlingstein et al., 2006; Todd-Brown et al., 2012; Kumar et al., 2013; Rafique et al., 2014).

The structural analysis of modeled C storage and residence time addressed in this study identifies the sources of variations at each step of entire C cycle. There are several studies (Friedlingstein et al., 2006) on climate-carbon feedback mechanism which are largely characterized with uncertainty in results. This study has a potential

to explain the models variations in a mechanistic way by tracing the information of NPP partitioning, C transfer, C storage and residence time in each C pool. The careful examination of the model structures, in terms of the number of C pools, C allocation and transfer coefficients, largely help in characterizing the models behavior. There are several studies on data assimilation (Zobitz et al., 2011) and bench mark analysis but always lacked the proper explanation in identifying the sources of variations and parameters identification. This study provides useful information for data assimilation, benchmark analysis and future model development by evaluating the relative importance of model components and source of variations. The traceability analysis presented here can be extended to include other biogeochemical models. However, additional research is required to further explain the causes of the differences among these models. One way to elaborate the analysis is to further examine the effects of environmental scalars and environmental forcing data which strongly influence the C residence time and transfer from one pool to another. Beyond this proposed study, the Markove Chain Monte Carlo (MCMC) technique is also helpful to quantify the individual contribution of model structure and parameterization in causing variations in modeled results.

## 5 Summary and conclusion

The NPP and C residence time have a strong influence on C storage capacity. Extensive research has been conducted on NPP dynamics, but the C residence time is mostly overlooked. This study decomposes C storage and residence time into traceable components simulated by three commonly used global land models: CABLE, CLM3.5-CASA and CLM4. We observed a wide difference in the spatial distribution of NPP, C storage and C residence time amongst the models; however, the total C storage amongst the models was relatively similar. The structural analysis of the models revealed that the total C storage in the plant and soil components of CABLE is closest with the observed data. The plant component in CABLE stored more C in the root tis-

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sues, whereas, CLM3.5-CASA and CLM4 stored more C in the woody tissues. Overall for the entire ecosystem C cycle, CLM3.5-CASA displayed a fast turnover time, followed by CLM4 and CABLE. The variation in C storage and C residence time between the models can be explained by the NPP allocation, model's structures and C transfer coefficients. CABLE allocates more C to root tissues; CLM3.5-CASA to leaf and CLM4 to fine root and leaf tissues. This allocation pattern resulted in more recalcitrant C in CABLE.

Based on the number of C pool, we can characterize CABLE, CLM3.5-CAS and CLM4 as a simple, moderate and complex model, respectively. CABLE performed the best in terms of C storage capacity in the plant and soil components, followed by CLM3.5-CASA and CLM4 respectively. The results depicted that the simple model performed better. In CABLE, CLM3.5-CASA and CLM4, large differences were observed in the transfer of C among the pools and their corresponding respiratory fluxes. This difference substantially affected the respective C pool size and residence time. Throughout the C cycle, CLM4, in comparison to the other two models, respired relatively less C as well as transferred more C amongst the pools. The structural analysis of the modeled C storage and C residence time addressed in this study, proved helpful in characterizing the behavior of the models. The results of this research will provide valuable information for the future study of model development, data assimilation and benchmark analysis. However, further study on the effect of environmental scalars and climate forcing is highly recommended, as they may have a strong impact on the C transfer among pools.

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**Table 1.** Salient features of the global land models CABLE, CLM3.5-CASA and CLM4 used in this study of model structural analysis.

Model Abbreviation	Model Name	Spatial Range	Spatial Resolution	Climate Forcing	Spin up Method	No. of Vegetation C Pools	No. of Litter Pools	No. of Soil C Pools	References
CABLE	CSIRO Atmosphere Biosphere Land Exchange	Global	1° × 1°	Wang et al. (2010)	SASU	3	3	3	Wang et al. (2010) Xia et al. (2012)
CLM-CASA	Community Land Model (version 3.5) with Carnegie-Ames-Stanford Approach	Global	2.81° × 2.81°	Qian et al. (2006)	SASU	3	6	3	Oleson et al. (2008) Doney et al. (2006)
CLM4	Community Land Model (version 4)	Global	0.9° × 1.25°	Qian et al. (2006)	Traditional	18	4	4	Thornton et al. (2009) Gent et al. (2011)

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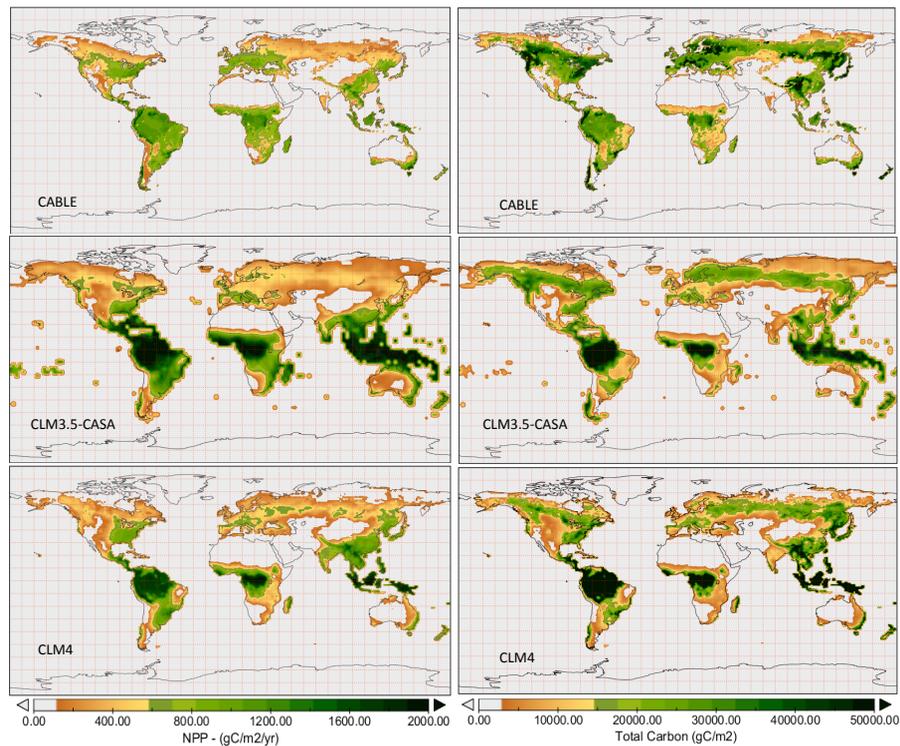
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**Figure 1.** Spatial distribution of simulated net primary productivity (NPP) and total ecosystem carbon storage in global land models CABLE, CLM3.5-CASA and CLM4.

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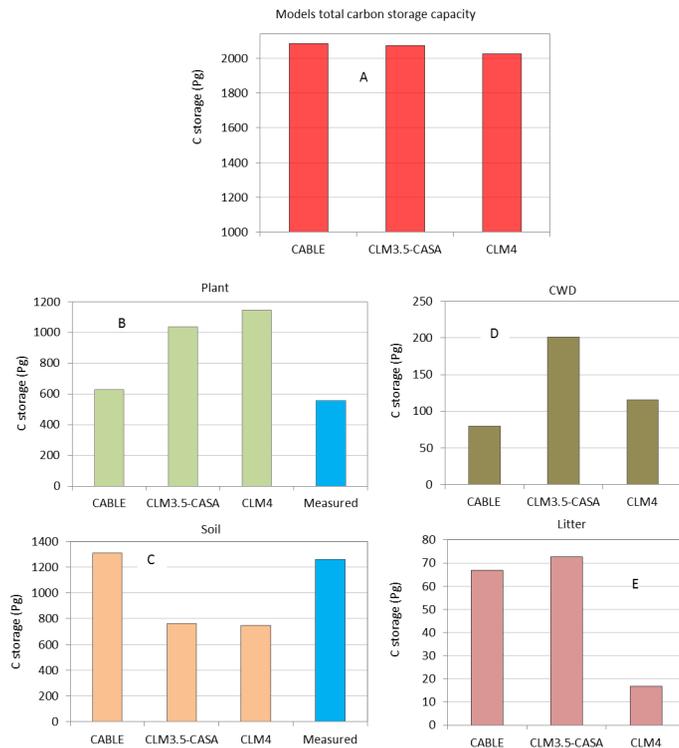
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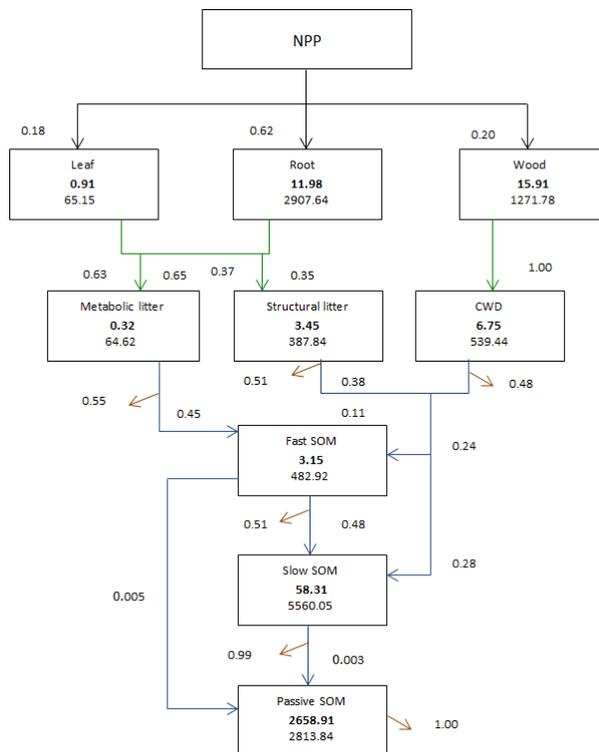


**Figure 2.** Comparison of carbon storage capacity among global land models CABLE, CLM3.5-CASA and CLM4. The results are reported at **(A)** Total carbon storage, **(B)** plant, **(C)** soil, **(D)** coarse woody debris (CWD) and **(E)** litter levels. The plant and soil carbon storage are also compared with available observed data. The total modeled carbon storage is the sum of plant, soil, CWD and litter pools.

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**Figure 3.** Schematic diagram showing the carbon cycle in CSIRO Atmosphere Biosphere Land Exchange (CABLE) model. Black line 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 carbon among litter and soil carbon pools while the brown lines represent the respiration fluxes. The bold numbers in each pool show the carbon residence time (years) while other number represents the carbon storage capacity in unit of  $\text{g C m}^{-2}$ .

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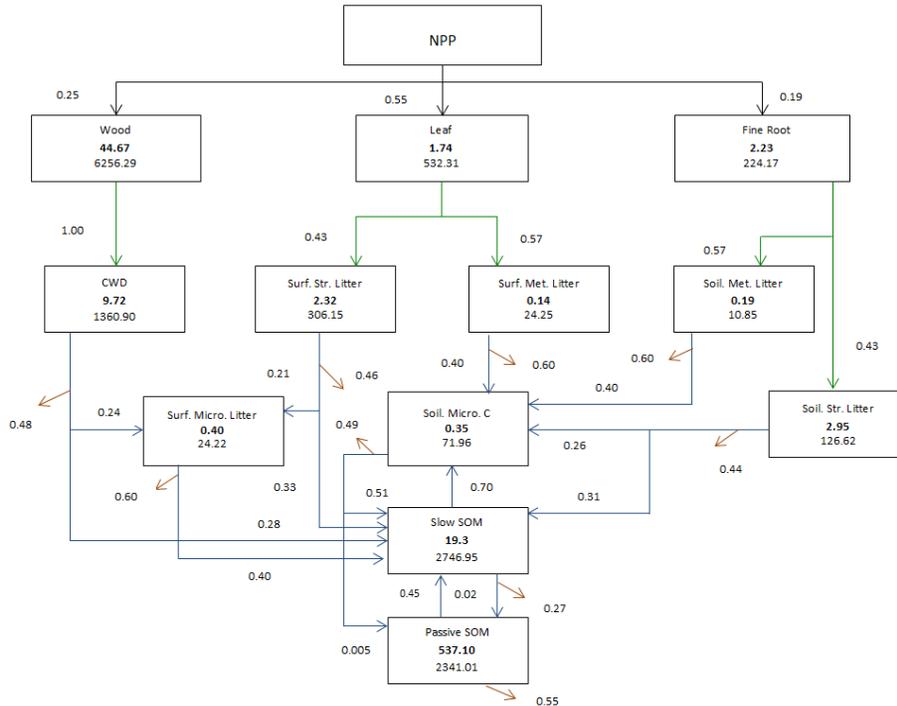
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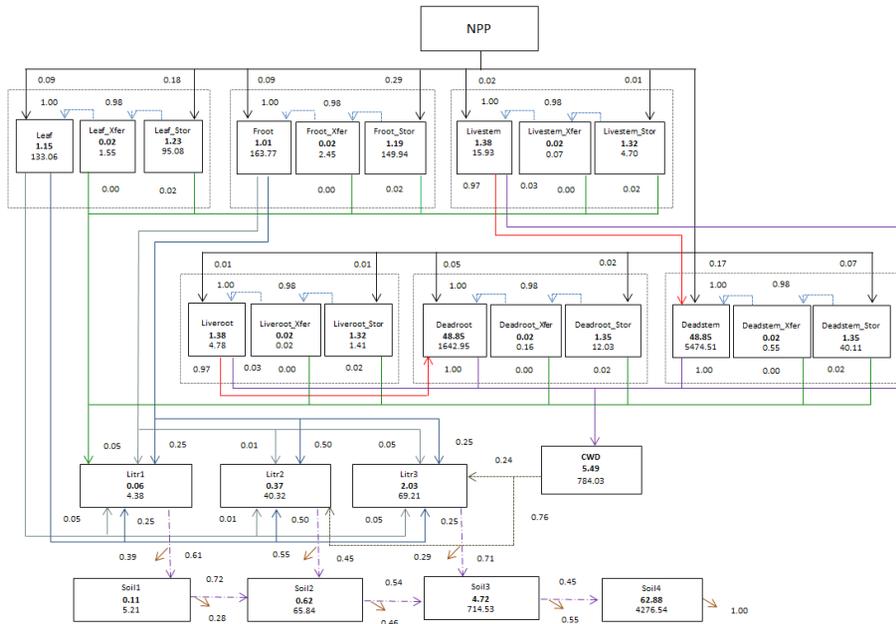
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**Figure 4.** Schematic diagram showing the carbon cycle in Community Land Model (CLM3.5-CASA). Black lines and corresponding numbers show the partitioning coefficients in plant pools. Green lines and corresponding numbers show the mortality fluxes of live tissues. Blue lines illustrate the flow of carbon among litter and soil carbon pools while the brown lines show the respiration fluxes. The bold numbers in each pool show the carbon residence time (years) while other number represents the carbon storage capacity in unit of  $\text{g C m}^{-2}$ .



**Figure 5.** Schematic diagram showing the carbon cycle in community land model (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 carbon transfer from storage to displayed carbon pools. Red lines and corresponding number represent turnover of live tissues in to 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 pink lines show the mortality of woody tissues into coarse woody debris (CWD) pool. Dotted pink lines illustrate the flow of carbon among litter and soil carbon pools while the brown color lines show the respiration fluxes. The bold numbers in each pool show the carbon residence time (years) while other number represents the carbon storage capacity in unit of  $g C m^{-2}$ .

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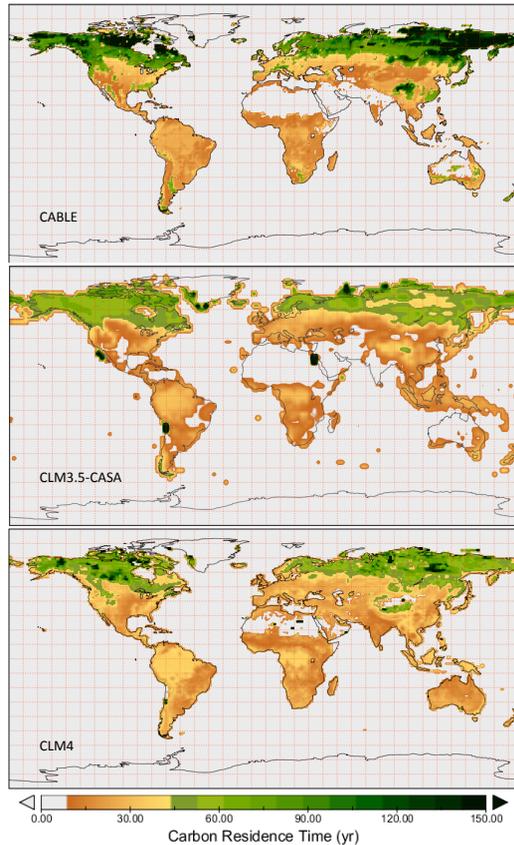
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**Figure 6.** Spatial distribution of simulated total ecosystem carbon residence time in global land models CBLE, CLM3.5-CASA and CLM4.

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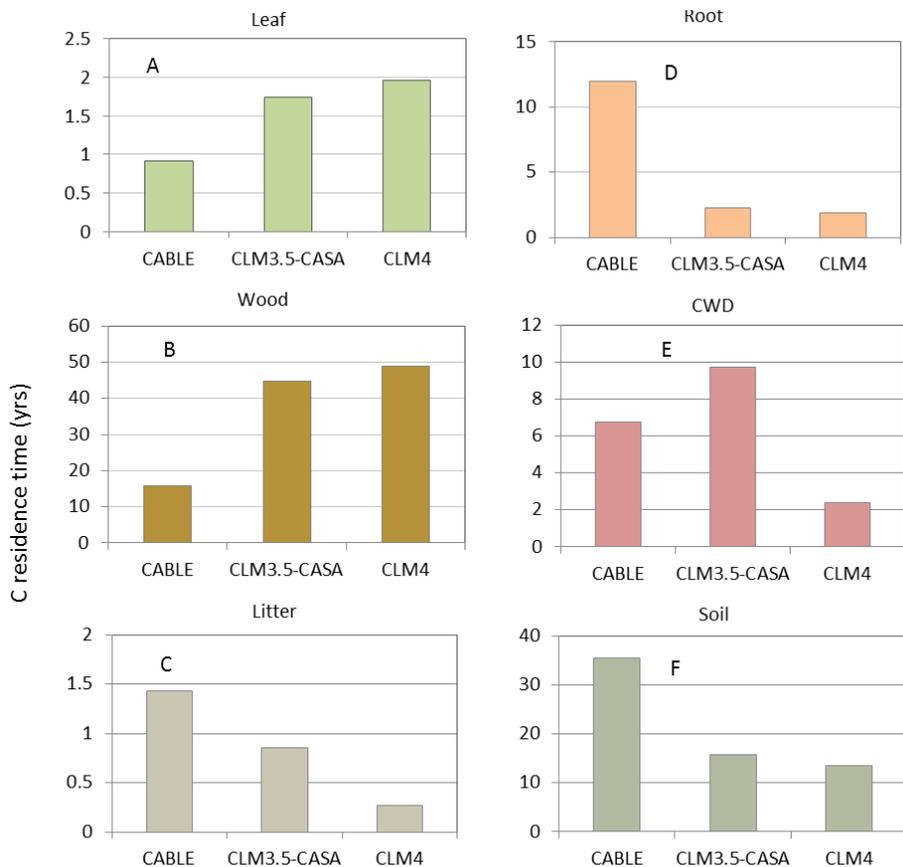
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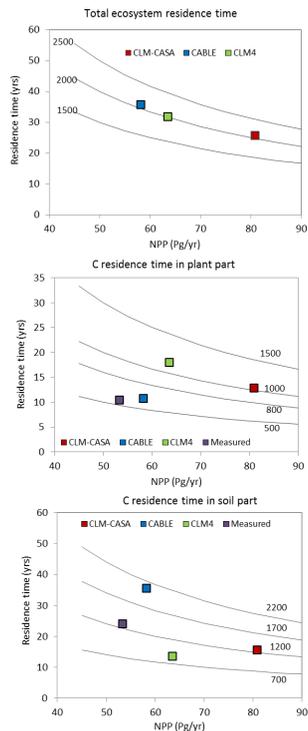




**Figure 7.** Comparison of carbon residence time among global land models CABLE, CLM3.5-CASA and CLM4. The results are aggregated from individual carbon pools to **(A)** leaf, **(B)** wood, **(C)** litter, **(D)** root, **(E)** coarse woody debris (CWD), and **(F)** soil.

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**Figure 8.** Scatter plot of carbon residence time in relation to net primary productivity (NPP) observed in three global land models CABLE, CLM3.5-CASA and CLM4. **(A)** Shows the total ecosystem residence in relation to total NPP, **(B)** shows the total carbon residence time of plant part (vegetation) in relation to total NPP, and, **(C)** shows the total carbon residence time of soil part in relation to total NPP. Contour lines represent the carbon storage capacity at given NPP and carbon residence time.

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