Impact of changes in climate and CO₂ on the carbon-sequestration potential of vegetation under limited water availability using SEIB-DGVM version 3.02

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Abstract

Documenting year-to-year variations in carbon-sequestration potential in terrestrial ecosystems is crucial for the determination of carbon dioxide (CO₂) emissions. However, the magnitude, pattern and inner biomass partitioning of carbon-sequestration potential, and the effect of the changes in climate and CO₂ on inner carbon stocks, remain poorly quantified. Herein, we use a spatially explicit individual based-dynamic global vegetation model to investigate the influences of the changes in climate and CO₂ on the enhanced carbon-sequestration potential of vegetation. The modelling included a series of factorial simulations using the CRU dataset from 1916 to 2015. The results show that CO₂ predominantly leads to a persistent and widespread increase in above-ground vegetation biomass carbon-stocks (AVBC) and below-ground vegetation biomass carbon-stocks (BVBC). Climate change appears to play a secondary role in carbon-sequestration potential. Importantly, with the mitigation of water stress, the magnitude of the above- and below-ground responses in vegetation carbon-stocks gradually increases, and the ratio between AVBC and BVBC increases to capture CO₂ and sunlight. Changes in the pattern of vegetation carbon storage was linked to regional limitations in water, which directly weakens and indirectly regulates the response of potential vegetation carbon-stocks to a changing environment. Our findings differ from previous modelling evaluations of vegetation that ignored inner carbon dynamics and...
demonstrates that the long-term trend in increased vegetation biomass carbon-stocks is driven by CO$_2$ fertilization and temperature effects that are controlled by water limitations.

1 Introduction

As a result of the changes in climate and atmospheric carbon dioxide (CO$_2$), the terrestrial ecosystem carbon cycle exhibits remarkable trends in interannual variations, which induce uncertainty in estimated carbon budgets (Erb et al., 2018; Keenan et al., 2017). Recent studies assessing interannual fluctuations in terrestrial carbon sinks have shown that the land carbon cycle is the most uncertain component of the global carbon budget (Ahlstrom et al., 2015; Piao et al., 2020; Jung et al., 2017; Humphrey et al., 2018; Gentine et al., 2019; Humphrey et al., 2021). These uncertainties result from an incomplete understanding of vegetation biomass carbon production, allocation, storage, loss, and turnover time (Bloom et al., 2016).

The extent and distribution of vegetation carbon storage is central to our understanding of how to maintain a balanced land carbon cycle. Changes in terrestrial vegetation carbon storage have a significant effect on atmospheric CO$_2$ concentrations and determine whether biomes become a source or sink of carbon (Erb et al., 2018; Humphrey et al., 2018; Terrer et al., 2021). Therefore, investigating the processes producing changes in carbon storage is key to improving the accuracy of estimated terrestrial carbon budgets, and to tap the greenhouse-gas moderation potentials of vegetation (Ipcce, 2007; Roy et al., 2001).

The response of vegetation carbon storage to greenhouse effects results from two mechanisms, direct effects of CO$_2$ on photosynthesis and indirect effects of changes in climate change and CO$_2$ on photosynthesis, respiration, and sequestration (Schimel et al., 2015; Gentine et al., 2019; Cheng et al., 2017). Since the beginning of industrialization, there has been a noticeable enhancement in the capacity of sequestering carbon, which is needed for stabilizing greenhouse gas concentrations (Chen et al., 2019; Pan et al., 2011; Le Noé et al., 2020; Magerl et al., 2019; Bayer et al., 2015; Harper et al., 2018). This increase has coincided with a widespread change in other vegetation features, including a positive increase in annual gross primary productivity and a greening of the biosphere (Madani et al., 2020; Zhu et al., 2016). The spatiotemporal distribution and environmental drivers in carbon-sequestration potential have been well documented on the basis of model estimates and satellite-based assessments (Erb et al.,
In contrast, the variability of above- and below-ground partitioning of carbon-sequestration potential has not been extensively studied. Without an accurate assessment of the dynamics of each fraction, attribution of carbon-sequestration potential to environmental drivers is highly uncertain. Consequently, partitioning potential vegetation carbon storage and revealing its inner processes are essential to accurately comprehend the current state of carbon sequestration capacity and predict how it will change in the future, both of which are key instruments in revealing the influence of various drivers on the enhancement of carbon-sequestration potential.

The variability in vegetation carbon flux is also linked to terrestrial water availability (Gentine et al., 2019; Seo and Kim, 2019). Thus, potential water limitations impart another constraint on the global ecosystem carbon cycle. Typically, increasing water stress limits the response magnitude of carbon uptake rates through a down-regulation of stomatal conductance (Humphrey et al., 2021). Trees and herbs are tuned to allocate higher carbon-flux to roots when mitigating for the adverse effects of limited water availability (Friedlingstein et al., 1999). Water availability controls both carbon allocation and storage and can potentially transform regions characterized by a negative response to climate to regions exhibiting a positive response. For example, warming has a negative effect on the percentage of roots in dry regions and increases the ratio of above- versus belowground biomass in wet regions (Ma et al., 2021). This is particularly apparent in tropical regions, where variations in water availability can result in different responses in the processes involved in the carbon cycle (Liu et al., 2017). The differences in the response mechanisms influencing the vegetation carbon flux among different hydrological regions is related to plant oversensitivity to hydrological gradients. Thus, it is important to systematically investigate the distinct responses of carbon-sequestration potential to changes in climate and CO2 under differing conditions of water stress.

As documented above, many studies have investigated the integral changes in regional and global terrestrial storage of carbon, while few studies have examined trends in the partitioning of carbon storage.
by vegetation biomass. Large gaps in our knowledge of the effects of various drivers on the partitioning of carbon-stocks in vegetation biomass remain. Importantly, an increase in the magnitude of water stress may dramatically change the impact of these drivers on above- versus below-ground partitioning of carbon-sequestration potential (Ma et al., 2021). Evaluating the response pattern of carbon-stocks to various drivers under conditions of limited water is elemental for clearly documenting the response mechanism of vegetation carbon-sequestration potential.

Here, we use a spatially explicit individual-based dynamic global vegetation model (SEIB-DGVM), along with the root-shoot ratio method (R/S) to (1) systematically determine the long-term variability of carbon-sequestration potential and understand its response mechanisms, and (2) estimate trends in partitioning of potential biomass carbon-stocks of vegetation biomass. Throughout this study, the potential biomass carbon-stock is recognized as a proxy for the potential of carbon-sequestration by natural vegetation. Using a set of factorial simulations to isolate responses to environmental change, we analyse the contributions of multiple driving factors to the trends of two fractions of carbon-stocks at large scales individually. We then conceptualize the role of water availability through an aridity index (AI), in which hydrological regions are subdivided by their degree of aridity. By comparing the differences in the magnitude of response between the fractions of above- and below-ground carbon-stocks for varying degrees of water availability, we assess the effect of water limitations on the response pattern of potential carbon-stocks to changes in climate and CO₂.

2 Model description, experimental design, observational data, and evaluation metrics

In this section, we provided a list of data source (Sect. 2.1), an overview of the modelling concept (Sect. 2.2), the representation of biomass carbon-stock partitioning in the SEIB-DGVM (Sect. 2.3), an overview of the experimental scheme used in the model simulations (Sect. 2.4), and the validation of model results (Sect. 2.5).

2.1 Forcing Data

Long-term daily meteorological time-series data are required to run model simulations, including precipitation, daily range of air temperature, mean daily air temperature, downward shortwave radiation,
downward longwave radiation, wind velocity and relative humidity. These data were obtained from the Climatic Research Unit (CRU) time series 4.00 gridded dataset (degree 0.5°) for the period 1901–2015 (Harris et al., 2020). Because the CRU dataset is a monthly based dataset, the monthly meteorological data were converted into daily climatic variables by supplementing daily climatic variability within each month using the National Centre for Environmental Prediction (NCEP) daily climate dataset. The NCEP data, displayed using the T62 Gaussian grid with 192 × 94 points, was interpolated into a 0.5° grid (which corresponds to the CRU dataset) using a linearly interpolation method. By combining the CRU data, with the interpolated NCEP dataset, we were able to directly obtain the most of driving meteorological data (details in Sato et al. (2020)). Neither the CRU nor NCEP datasets included downward shortwave and longwave radiation. Thus, daily cloudiness values in the NCEP were used to calculate radiation values using empirical functions (Sato et al., 2007). These data were all aggregated to a daily timescale with 0.5° resolution to run SEIB-DGVM.

Atmospheric CO₂ concentrations were collected from Sato et al. (2020), which contains reconstructed CO₂ concentrations between 1901 and 2015. The statistical reconstruction of global atmospheric CO₂ was used in this analysis. These reconstructions were based on present annual CO₂ concentrations recorded from the Mauna Loa monitoring station. These data assume atmospheric CO₂ concentration was 284 ppm in 1750, and statistically interpolates atmospheric CO₂ concentrations to fill the gap from 1750 to 2015.

The physical parameters of the soil used in the model include soil moisture at the saturation point, field capacity, matrix potential, wilting point and albedo. These data were obtained from the Global Soil Wetness Project 2.

2.2 Overview of modelling concept in SEIB-DGVM

Model SEIB-DGVM version 3.02 (Sato et al., 2020) was employed in this study. This is a process-based dynamic global vegetation model driven by meteorological and soil data. It is an explicit and computationally efficient carbon cycle model designed to simulate transient effects of environmental change on terrestrial ecosystems and land-atmosphere interactions. It describes three groups of processes: land-based physical processes (e.g., hydrology, radiation, aridity), plant physiological processes (e.g.,
photosynthesis, respiration, litter), and plant dynamic processes (e.g., establishment, growth, mortality).

Twelve plant functional types (PFTs) were classified. During the simulation, a sample plot was established at each grid box, and then the growth, competition, and mortality of each the individual PFTs within each plot were modelled by considering the specific conditions for that individual as it relates to other individuals that surround it (Sato et al., 2007).

SEIB-DGVM treats the relationships between soil, atmosphere, and terrestrial biomes in a consistent manner, including the fluxes of energy, water, and carbon. Based on specified climatic conditions and soil properties, SEIB-DGVM simulates the carbon cycle, energy balance, and hydrological processes. SEIB-DGVM utilizes three computational time steps: (1) a daily time step for all physical and physiological processes, including soil decomposition and tree growth, (2) a monthly time step for tree growth, and (3) an annual time step for tree establishment and death. The simulated unit of the model is a 30 m × 30 m spatially explicit ‘virtual forest’. A grass layer was placed under the woody layer, and provides for a comprehensive, spatially explicit quantification of terrestrial carbon sinks and sources.

The soil depth was set at 2 m and was divided into 20 layers, each with a thickness of 0.1 m. The photosynthetic rate of a single-leaf was simulated following a Michaelis-type function (Ryan, 1991). Respiration was divided into two types: growth respiration and maintenance respiration. Growth respiration is defined as a construction cost for plant biosynthesis, which is quantified by the chemical composition of each organ (Poorter, 1994). Maintenance respiration of live plants occurs every day regardless of the phenological phase, and is controlled by the temperature and nitrate content of each organ (Ryan, 1991). Atmospheric CO₂ was envisioned to be absorbed by photosynthesis of woody PFTs and grass PFTs. This assimilated carbon flux was then allocated into all the plant organs (leaf, trunk, root, and stock), where maintenance respiration and growth respiration occur. The hydrology module treats precipitation, canopy interception, transpiration, evaporation, meltwater, and penetration.

SEIB-DGVM differs from other dynamic global vegetation models in that it is a biogeochemical model that represents plant structure in three-dimensions. This representation of vegetation dynamics has two advantages. First, it directly uses in-situ data about PFT dynamics and structure as tuning or validation data, without adding additional assumptions. Second, sunlight and other resources are distributed among
individuals without human disturbances, leading to a more properly calculated and accurate representation of the responses of potential vegetation biomass to external environmental change. Therefore, SEIB-DGVM, in general, effectively represents plant competition and function dynamics under environmental change (Sato et al., 2007).

2.3 Carbon-stock of vegetation biomass partitioning

2.3.1 Parameterization of daily allocation

Flexible allocation schemes about resources and biomass are set up in the framework of the SEIB-DGVM biogeochemical model. Atmospheric CO₂ is assimilated by the photosynthesis of both woody and grass foliage, and then is added into the non-structural carbon of the plant. This non-structural carbon of photosynthetic production is allocated to all the plant organs (foliage, trunk, root, and stock), supplying what is needed for the maintenance and growth of each organ. When the non-structural carbon is greater than 0 during the growth phase, the following dynamic carbon allocation is executed for each individual plant at the daily time scale, such that:

1. When the fine root biomass (massroot) of wood or grass does not satisfy minimum requirements for fulfilling functional balance (massleaf/FRratio), the mass of non-structural carbon is allocated to the root biomass to supplement the deficit. Here, massleaf is the leaf biomass, and FRratio is the ratio of massleaf to massroot satisfying the functional balance.

2. The stock biomass is supplemented until it is equal to leaf biomass. This scheme is active after the first thirty days of the growing phase.

3. Woody leaf biomass is constrained by three limitations of the maximum leaf biomass, which are calculated as follows:

\[
\max_1 = \left( \text{crown area} + \pi \text{crown diameter} \times \text{crown depth} \right) \frac{L \times \text{max}_{\text{SLA}}}{\text{SLA}} \\
\max_2 = A L M_1 \frac{n (d b h_{\text{heartwood/2}} + d b h_{\text{sapwood/2}})^2 - n (d b h_{\text{heartwood/2}})^2}{\text{SLA}} \\
\max_3 = \frac{\text{mass}_{\text{available}}}{\text{RGF}} \\
\text{mass}_{\text{leaf}} = \min (\max_1, \max_2, \max_3)
\]

where max₁, max₂, and max₃ are, respectively, maximum leaf biomass for a given crown surface area, cross-sectional area of sapwood, and non-structural carbon, SLA is a constant of PFTs leaf area (m² g⁻¹).
\( L_{A_{\text{max}}} \) is maximum leaf area of PFTs per unit biomass (m² m⁻²), and \( A_{LM1} \) represents the area of transport tissue per unit biomass, and is a constant (dimensionless). If the mass_{leaf} is less than the minimum (\( \text{max}_1, \text{max}_2, \text{max}_3 \)), the mass of non-structural carbon is allocated into leaf biomass to supplement the deficit.

Grass leaf biomass is supplemented until the leaf area index of grass equals the optimal leaf area index, which are calculated as:

\[
\text{\( \text{lat}_{\text{opt}} = \frac{\ln \text{par}_{\text{grass}}}{\ln \frac{\text{par}_{\text{lue}}}{\text{cost/sLA} \times \epsilon K}} \)}
\]

(5)

where \( \text{lat}_{\text{opt}} \) is optimal leaf area index (m² m⁻²), \( \text{par}_{\text{grass}} \) is the grass photosynthetically active radiation (\( \mu \text{mol photon m}^{-2} \text{s}^{-1} \)), \( \text{par}_{\text{lue}} \) is the light-saturated photosynthetic rate (\( \mu \text{CO}_2 \text{m}^{-2} \text{s}^{-1} \)), \( \text{lua} \) is the light-use efficiency of photosynthesis (mol CO₂ mol photon⁻¹), \( \text{cost} \) is the cost of maintaining leaves per unit leaf mass per day (g \( \text{DM g DM}^{-1} \text{ day}^{-1} \)), \( \text{dlen} \) is day length (hour), and \( \epsilon K \) is light attenuation coefficient at midday.

(4) When non-structural carbon is less than 10 g dry mass (DM) PFT⁻¹ or annual NPP is less than 10 g DM PFT⁻¹ in the previous year, the following daily simulation processes (5–6) will be skipped.

(5) When total woody biomass is more than 10 kg DM, which defines the minimum tree size for reproduction, 10% of non-structural carbon is transformed into litter.

(6) During the simulation of trunk growth, the remaining structural carbon is allocated to sapwood biomass. There is no direct allocation to heartwood, which is transformed slowly from sapwood biomass.

For grass PFTs biomass, the densities of all organs comprising the biomass never decline below 0.1 g DM m⁻² even if the environment is deteriorated for grass survival. A more detailed description of SEIB-DGVM is given by Sato et al. (2007).

Terrestrial water availability represents a significant source of variability in the ecosystem carbon cycle (Humphrey et al., 2021; Humphrey et al., 2018; Ma et al., 2021). To control plant phenology and the rate of photosynthesis as a function of the limitation in terrestrial water, the physiological status of the limitation of terrestrial water is calculated as:

\[
\text{\( \text{stat}_{\text{water}} = \frac{\max(\text{pool}_{\text{w}(n)} / \text{Depth}_{(n)}, \text{pool}_{\text{w}(2)}/\text{Depth}_{(2)}) - \text{W}_{\text{will}}}{\text{W}_{\text{f}} - \text{W}_{\text{will}}} \)}
\]

(6)

where \( \text{stat}_{\text{water}} \) is the physiological status of the terrestrial water limitation, which ranges between 0.0–1.0, dimensionless, \( \text{pool}_{\text{w}(n)} \) is the water content in soil layer \( n \), mm, \( \text{Depth}_{(n)} \) is depth of the soil layer.
n, mm, $W_{\text{wile}}$ is soil moisture at the wilting point, m m$^{-1}$, and $W_{f}$ is soil moisture at field capacity, m$^{-1}$. When the temperature of all soil layers is less than 0°C, $\text{stat}_{\text{water}}$ is equal to 0.

### 2.3.2 Carbon-stock partitioning method

According to the flexible allocation scheme, SEIB-DGVM allocates and stores the biomass carbon in four pools of woody PFT (foliage, trunk, root, and stock) and three pools of grass PFT (foliage, root, and stock). To investigate the fractional variability of carbon-sequestration potential between the pools, we partitioned potential vegetation carbon-stocks based on the physiological function of the plant (Figure A1). The root-shoot ratio (R/S) has been widely used to investigate the relationship between aboveground vegetation biomass to belowground vegetation biomass and is considered an important variable in the terrestrial ecosystem carbon cycle (Zhang et al., 2016). In this study, we adjusted the method of calculating the R/S ratio by distinguishing between the aboveground vegetation biomass carbon-stock (AVBC) and the belowground vegetation biomass carbon-stock (BVBC). AVBC includes biomass carbon from woody foliage, woody trunk, and grass foliage, while BVBC includes biomass carbon from woody fine roots and grass fine roots, excluding the stock pool. Thus,

$$AVBC = \frac{W_{\text{mass}_{\text{leaf}}} + W_{\text{mass}_{\text{trunk}}} + G_{\text{mass}_{\text{leaf}}}}{W_{\text{mass}_{\text{root}}} + G_{\text{mass}_{\text{root}}}} \times 100\%$$

where $AVBC$ is aboveground vegetation biomass carbon-stock (kg C m$^{-2}$), $BVBC$ is belowground vegetation biomass carbon-stock (kg C m$^{-2}$), $W_{\text{mass}_{\text{leaf}}}$ is the leaf biomass carbon-stock of wood (kg C m$^{-2}$), and $W_{\text{mass}_{\text{trunk}}}$ is the trunk biomass carbon-stock of wood (kg C m$^{-2}$), including both branch and structural roots. This biomass is simplistically attributed to aboveground organs and is used primarily to support the plant. $G_{\text{mass}_{\text{leaf}}}$ is the leaf biomass carbon-stock of grass (kg C m$^{-2}$), whereas $W_{\text{mass}_{\text{root}}}$ and $G_{\text{mass}_{\text{root}}}$ are functional root (fine roots) biomass carbon-stocks of wood and grass, separately (kg C m$^{-2}$), which absorb water and nutrition from soil.

### 2.4 Experimental design

#### 2.4.1 Setup of model runs

SEIB-DGVM simulations begin with seeds of selected plant function types planted in bare ground. The plant functional types are favored for establishment by the environmental conditions in each grid cell. We inputted the transient climate data from 1901 to 1915 to spin up the model in a repetitive loop.
obvious trend in climatic factors was observed during this period (Tei et al., 2017). A spin-up period of 1050 years was necessary to bring the terrestrial vegetation carbon cycle into a dynamic equilibrium. To reach quasi-equilibrium in the vegetation biomass, about 1000 years of simulation was required as a spin-up procedure.

### 2.4.2 Factorial simulation scheme

**Table 1.** List of factorial simulations used in this study

<table>
<thead>
<tr>
<th>Factorial simulation</th>
<th>CO$_2$ fertilization</th>
<th>Precipitation</th>
<th>Temperature</th>
<th>Radiation</th>
<th>Other drivers</th>
</tr>
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<tbody>
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</table>

Note: In factorial simulation S1, historical atmospheric CO$_2$ concentration and historical climate fields from the CRU data set were used. In simulation S2, only historical atmospheric CO$_2$ concentration was used, and climate variables of the transient period (1901–1915) were repeatedly input. In simulation S3 (or S4, S5), only historical atmospheric CO$_2$ concentrations and precipitation (or temperature, radiation) were input, and climate variables of the transient period (1901–1915) were repeatedly input. In the last simulation S6, historical atmospheric CO$_2$ concentrations and other climate variables were input, excluding precipitation, temperature, and radiation.

To further quantify the relative contributions of varying atmospheric CO$_2$ concentrations, precipitation, temperature, and radiation, we performed six factorial simulations after the spin-up procedure using different input variables between 1916 and 2015 (Table 1). Other drivers included wind velocity and relative humidity. Consistent with previous studies (Zhu et al., 2016; Piao et al., 2006), the contribution of CO$_2$ to the trend in carbon-stocks trend was defined as the ratio of the carbon-stock increase from simulation S2 to that of simulation S1. The contributions of precipitation, temperature, radiation, and other factors were calculated by subtracting simulation S2 from each corresponding simulation (S3, S4, S5, S6, respectively), then dividing by simulation S1.

### 2.4.3 Non-parametric test methods

Each driving factor (atmosphere CO$_2$, precipitation, temperature, and radiation) has a different influence on the carbon-stock, so it is difficult to make a simple pre-assumption about the population distribution pattern for factorial simulations. We used the non-parametric Mann-Kendall and Sen’s slope estimator statistical tests (Gocic and Trajkovic, 2013) to assess the ability of SEIB-DGVM to simulate the response...
patterns of carbon-sequestration potential to a change in climate and CO$_2$ concentrations. We regressed the simulated hundred-year mean global average carbon-stock time series to reveal the accumulative influences of the single variables based on the factorial simulations where only one or two drivers were varied. Detection trends of AVBC and BVBC for all driving factors performed statistically well (in agreement at the 95% confidence intervals), indicating this analytical method was suitable for trend attribution at the global scale.

2.4.4 Distinguishing hydrological regions

![Figure 1. Global spatial patterns of water availability.](https://doi.org/10.5194/gmd-2021-383)

Locally available water strongly regulates and limits the response of carbon-stocks to changes in climate and CO$_2$. We defined an aridity index (AI) to distinguish between the global hydrological regions for comparing the long-term trend in carbon-stocks over different hydrological environments, and for quantifying the influences of each hydrological environment on the variations in the trends. The AI was defined as:

$$AI = \frac{\bar{P}}{\bar{ET}_p}$$ (8)

where $\bar{P}$ is the multiyear mean precipitation (mm year$^{-1}$), and $\bar{ET}_p$ is the multiyear mean potential evapotranspiration (mm year$^{-1}$), which was calculated by the Penman-Monteith model (Monteith and Unsworth, 1990). As in a previous study (Chen et al., 2019), five hydrological regions (Figure 1) were categorized based on an 115-year average AI (1901–2015): including a hyper-arid region (AI ≤ 0.05), arid region (0.05 < AI ≤ 0.2), semi-arid region (0.2 < AI ≤ 0.5), sub-humid region (0.5 < AI ≤ 0.65), and humid (AI > 0.65).
humid region (AI > 0.65).

3 Results and discussion

3.1 Evaluation of SEIB-DGVM

In terrestrial vegetation biomes, there is a high correlation between biomass carbon-stock density and NPP per unit (Erb et al., 2016; Kindermann et al., 2008) (Figure A1). Thus, we initially used NPP as a proxy of the carbon-stock to assess model accuracy. We obtained the dataset from the Ecosystem Model-Data Intercomparison (EMDI) working group, and then compared their data with modelled multiyear average NPP in the period of 1916-1999. The EMDI dataset is an ensemble from global ecological sites from 1901 to 1999 and is shown in Figure 2. The determined coefficient (R²) between EMDI observed and estimated multiyear average NPP of 669 in-situ observations is 0.54, which is significant at the p=0.01 level. The slope of the regressed line is 0.70 during the twentieth century.

Figure 2. Multiyear average NPP calculated by SEIB-DGVM and EMDI for the twentieth century. (a) EMDI global site distribution. Green rhombuses indicate the locations of the sites. (b)
Comparison of NPP calculated by SEIB-DGVM and EMDI. The solid line is the best fit curve; and the dashed line represents a perfect correspondence in the results of the two. However, \textit{in-situ} observations are sparse for global spatial-temporal validation. Therefore, we used the MOD17A3 products to further verify the simulated potential NPP from 2000 to 2015. These data were collected by the Moderate Resolution Imaging Spectroradiometer and are some of the most widely used data to assess the accuracy of global model simulations (Gulbeyaz et al., 2018). The potential vegetation refers to the hypothetical condition that would prevail in an assumed absence of anthropogenic activity, but under historical climate fields (Erb et al., 2018; Haberl et al., 2014). The potential NPP in the potential vegetation is defined as that the assimilated carbon stored in land vegetation without human disturbance under current environmental conditions (Erb et al., 2018). We resampled actual NPP data from MOD17A3 to a common spatial resolution (0.5°) by the majority method. Potential NPP-MOD17A3 data were extracted from typical NPP values in grids only covered by vegetation from actual NPP-MOD17A3 data. Regions covered by undisturbed vegetation were distinguished from a land vegetation cover map. Figure 3 shows that the modelled NPP from the SEIB-DGVM exhibited a high degree of consistency with the NPP-MOD17A3 data over the period ($R^2=0.62$, $p<0.05$). The general spatiotemporal agreement between the simulated NPP derived from SEIB-DGVM with \textit{in-situ} observations and derived from satellites reveals that it is reasonable to use the SEIB-DGVM simulations to evaluate the same mechanisms controlling global potential biomass carbon stocks of vegetation.

For obtaining potential NPP-MOD17A3 data, we collected a land-use dataset from MCD12C1 to make a vegetation cover map in the period of 2001–2015. We resampled the land cover map to a common

Figure 3. Spatial patterns in the potential NPP correlation coefficients between SEIB-DGVM and MODIS between 2001–2015. These data were used to validate SEIB-DGVM.
spatial resolution (0.5°), and extracted grids of covered vegetation to produce the land vegetation cover map (Figure A2). Cover types on the map include evergreen needleleaf forests, evergreen broadleaf forests, deciduous needleleaf forests, deciduous broadleaf forests, mixed forests, closed shrublands, open shrublands, woody savannas and grasslands.

Finally, the modelled result of potential vegetation biomass carbon-stock was compared with current existing data from the literature and state-of-the-art datasets. Figure 4 shows that the modelled results are within the range of potential carbon-stocks, which indicate that the SEIB-DGVM reliably simulated the carbon-stock dynamics.

**Figure 4.** Estimates of the potential vegetation biomass carbon-stock from the literature (parentheses), state-of-the-art datasets (brackets) and this study. Datasets are from the following studies: [1](Erb et al., 2018; Erb et al., 2007), [2](Bazilevich et al., 1971), [3](Saugier et al., 2001), [4](Erb et al., 2018; Bartholome and Belward, 2005), [5](Olson et al., 1983), [6](Erb et al., 2018; Pan et al., 2011), [7](Ajtay et al., 1979), [8](Erb et al., 2018; Ruesch and Gibbs, 2008), [9](Kaplan et al., 2011), [10](Shevliakova et al., 2009), [11](Kaplan et al., 2011), [12](Pan et al., 2013), [13](Prentice et al., 2011), [14](Erb et al., 2018; Erb et al., 2007), [15](Erb et al., 2018; West et al., 2010), [16](Hurtt et al., 2011). The red column is the SEIB-DGVM-modelled biomass carbon stocks used in this study.

### 3.2 Enhanced carbon-stocks and its fractions

A global time series of potential vegetation carbon-stocks and its partitioning fractions were modelled by the SEIB-DGVM between 1916–2015. The simulations were conducted at a spatial resolution of 0.5° and at a daily timescale using CRU and reconstructed atmospheric CO2 concentration data. We distinguished the changes of AVBC and BVBC from integral vegetation carbon-stocks. The historical temporal trends over the period are shown in Figure 5a. The potential vegetation carbon-stock (the year-
to-year accumulation of carbon in the terrestrial plant without external interference) exhibits a net increase of 119.26 ± 2.44 Pg C in the last century (± 2.44 represents monthly fluctuation in carbon within the year). This increasing trend exhibits a robust agreement with the slower increase in atmospheric CO₂ concentration (R²=0.88, p<0.001), suggesting that the carbon-stock is strongly affected by CO₂ fertilization. In addition, the positive correlation between the carbon-stock and CO₂ generally extends across all vegetation biomass partitions (AVBC+BVBC). After the value of the global terrestrial carbon-stock and trends were partitioned among the vegetation functional classes, we see that AVBC increases 116.18 ± 2.34 Pg C (or ~15.60%) and dominates the positive global carbon-stock trend; BVBC also increases 3.08 ± 0.14 Pg C (or ~18.03%) over the past century.

Figure 5. Global potential biomass carbon stocks of vegetation during the past 100 years. (a) The evolution of global potential biomass stocks (AVBC+BVBC), along with changes in biomass stocks that can be attributed to the variability and trend of AVBC and BVBC through the twentieth century. The red line represents the monthly value of AVBC, the blue line represents the monthly value of BVBC, and the pink line represents the annual value of potential vegetation carbon stock. (b, c) Zonal averaged sums of the annual AVBC and BVBC for latitudinal bands during the first decade; the averaged value (1916–1925, red line) and the last decade averaged value (2006–2015, blue line) shows the increased carbon stock capacity.

The global distributions of the decadal-average change in AVBC and BVBC are shown in Figures 5b and
5c, respectively. The significant historical changes in climate and CO₂ enhance the carbon-stock of the terrestrial ecosystem, and their positive influences are broadly distributed across a latitudinal north–south gradient. The latitudinal bands of increasing annual AVBC are mainly distributed in the tropic and boreal latitudes, a conclusion consistent with prior knowledge (Erb et al., 2018; Schimel et al., 2015). The decadal and inter-annual variabilities of AVBC are dominated by the tropical and semi-arid regions where large portions of the regions are highly productive (Ahlstrom et al., 2015; Poulter et al., 2014). There is a single peak in the spatial variation of annual BVBC (Figure 5c). BVBC exhibits robust growth at most latitudes, and it increases mainly in boreal latitudes.

### 3.3 Spatial variability in estimated AVBC and BVBC trends

Based on the carbon-stock partitioning method, we found that the integrated carbon-stock as well as the above- and belowground carbon-stocks over the period of 1916–2015 exhibited a remarkable spatial heterogeneity. Figure 6a shows that an increase in vegetation carbon-stocks occurred over regions and global aggregate levels during the entire study period. About 57.39% of the terrestrial grids exhibited an increase with a noticeable trend (p<0.05) in biomass carbon-stock; 53.82% of global grids possessed increases that were statistically significant at the p=0.01 level. To determine the contributions of each fraction (AVBC, BVBC) to the integral change in the potential vegetation carbon-stock, we partitioned and present the historical spatial and temporal patterns for each fraction separately (Figure 6b, 6c). AVBC contributes 97.33% to the total incremental change (116.18 ± 2.34 Pg C), with about 51.32% of the grids possessing a noticeable positive trend (p=0.01). Generally, spatial patterns of AVBC and the integral carbon-stock are consistent (Figure 6a, 6b), which further supports the argument that AVBC dominates the trend in carbon-stocks in most regions. Although the proportion of the total change in carbon-stocks is small (3.08 ± 0.14 Pg C), about 61.00% of the land surface shows an increase in BVBC; of these terrestrial grids, 55.81% was characterized by a significant p=0.01 increase.
Figure 6. Spatial patterns in the trends of potential vegetation carbon-stocks and their fractions from 1916 to 2015. Difference induced by changes in climate and CO₂ in terrestrial biomass carbon-stock (a), AVBC (b), and BVBC (c) during the historic period 1916–2015. (d) Trend in the AVBC/BVBC ratio from 1916 to 2015. The sub-graphs show the significant test results. The white bar indicates non-vegetated areas, or the trend is statistically insignificant (P >0.05). The blue bar indicates significantly increasing trends in the ratio and vice versa.

Biomass carbon allocation between above- and belowground vegetation organs reflect the changes in individual growth, community structure and ecosystem function, which are important attributes in the investigation of carbon-stocks and carbon cycling within the terrestrial biosphere (Hovenden et al., 2014; Fang et al., 2010; Ma et al., 2021). Under the influences of a changing climate and CO₂ concentrations, there is a slight increase in the ratio of global AVBC/BVBC; the rate of increase is 0.0171 yr⁻¹ in the last hundred years, which is significant at the 0.01 level (Figure 6d). Regions with noticeable increases in the ratio of AVBC to BVBC are mainly located in southern Africa, central South America, and northern Eurasia. Negative trends in AVBC/BVBC ratios are found in northern America, southern Europe, and tropical Africa.

3.4 Responses of AVBC and BVBC to environmental drivers

The responses of AVBC and BVBC to changes in climate and CO₂ are both positive at the global level (Figure 7a, 7c), although regionally, they exhibit both negative and positive responses (Figure 7b, 7d). Based on the results of factorial simulations and Mann-Kendall+Sen tests, CO₂ fertilization explains the largest proportion of the change in the carbon-stock, about 82.45% change in AVBC was positive (15.521 g C m⁻² yr⁻¹), whereas 89.28% of the change in BVBC was positive (0.435 g C m⁻² yr⁻¹). The separately simulated AVBC and BVBC increased by 80.98 Pg C and 2.66 Pg C with increasing atmospheric CO₂ concentrations (from 301.73 ppm in 1916 to 400.83 ppm in 2015). The other climatic drivers (precipitation, temperature, radiation, humidity, and wind speed) remained at baseline values. While the increase or decrease in the carbon-stock may be attributed to more than one driving factor, within any specified grid, the one with the highest contribution was the driver that consistently resulted in the highest...
increase or decrease in the carbon-stock for that grid. The spatial pattern illustrates that CO$_2$ dominates the variability in AVBC in 7.28% of the regions, including 1.21% of the regions that exhibited a negative change and 6.07% that exhibited a positive change. CO$_2$ dominates the variability in BVBC in 27.60% of the regions, including 1.73% of the regions that exhibited a negative change and 25.87% of regions with a positive change (Figure 7b, 7d). These trends are consistent with previous studies (Tharammal et al., 2019; Zhu et al., 2016; Keenan et al., 2017) in which positive trends occurred, especially for BVBC. The responses of terrestrial ecosystems to high CO$_2$ concentration are affected by vegetation species and the dynamic function of the vegetation carbon-stock. Due to the interaction between terrestrial vegetation and a changing environment, both photosynthesis and respiration of the vegetation also changed. To better absorb CO$_2$ and sunlight required for photosynthesis, vegetated regions are gradually covered by vegetation with higher plant height and wider leaf area, thereby adjusting their characteristic ecosystem functions (Anderson et al., 2010) (Figure 6d). Fractional dynamics of the carbon-stock (AVBC/BVBC) are widely used as a key indicator to investigate the responses of vegetation to environmental drivers, which also reflect the response strategies of vegetation in environments with different water limitations (Yang et al., 2010).

Figure 7. The proportion of change in the integrated vegetation biomass carbon stocks attributed to driving factors. Ratios of the driving factors of CO$_2$ fertilization effects (CO$_2$), climate change effects (CLI), precipitation (Pre), temperature (Tem), radiation (Rad) for AVBC (a) and...
BVBC (c) under the five scenarios using the Mann-Kendall and Sen's slope estimator statistical tests. Attribution of AVBC (b) and BVBC (d) dynamics to driving factors calculated as averages along 15° latitude bands. At local scales, the driving factors include CO₂, Pre, Tem, Rad, and other climate factors (OF). A ‘+’ symbol indicates a positive effect of the driving factor on carbon stock, and vice versa. The fraction of global area (%) that is predominantly influenced by the driving factors is shown at the top of the bar.

Climate change induced by the greenhouse effect explains part of the increase in carbon-stocks, but unlike CO₂ fertilization, climate has dramatic negative effects on some vegetated regions. Figure 7 illustrates that temperature is the largest climatic contributor to the change in AVBC (13.83%, 2.572 g m⁻² yr⁻¹), followed by precipitation (8.51%, 1.572 g m⁻² yr⁻¹) and radiation (−3.19%, −0.649 g m⁻² yr⁻¹). The spatial distribution shows that temperature predominantly influences the change in AVBC, influencing over 27.56% of the global vegetated regions, followed by precipitation (21.88%) and radiation (20.67%). Modelled BVBC trends based on the factorial simulations have similar spatiotemporal patterns to AVBC. The effects of temperature on BVBC are stronger than AVBC, because fine root tightly correlates with temperature (Gill, 2000). Meanwhile, there is a difference in the negative contribution of precipitation to the change in BVBC at the global level (−2.76%, −0.013 g m⁻² yr⁻¹). It should be noted that trends in the global carbon-stock can be largely attributed to the influences of CO₂, precipitation, temperature, and radiation (Figures 8, 9). Nonetheless, at the regional scale, the contributions of other factors should be considered, such as humidity and wind speed. The effects of these other factors dominate trends in AVBC in over 16.05% of the regions that increased and 6.57% of the regions that decreased. In the case of changes in BVBC, other factors were dominant drivers in over 14.75% of the regions that increased and 3.57% of regions that decreased. Previous studies have pointed out that the interannual variation of the terrestrial carbon-stock caused by releasing or sequestering carbon is sensitive to anomalous changes in water availability and light use efficiency (Madani et al., 2020; Humphrey et al., 2018). However, multidecade observational data revealed that there was not a dramatic and consistent variant in the land surface precipitation and radiation data series (Sun et al., 2012; Wild et al., 2005). It appears that the influences of precipitation and radiation on short-term variations in the carbon-stocks were temporally compensated for by offsetting changes of AVBC, BVBC, and AVBC/BVBC in the long-term trend. The accumulated influence of climate warming induces dramatic changes in the carbon-stock at a global scale. Thus, we suggest that temperature dominates the long-term trends in the carbon-stock among climatic drivers, while a compensatory effect exists in the long-term
change in the carbon-stock induced by precipitation and radiation.

Figure 8. Potential AVBC trend maps during the period of 1916 to 2015 under different factorial simulations. (a) CO$_2$ driving factorial simulation; (b) CO$_2$+precipitation driving factorial simulation. (c) CO$_2$+temperature driving factorial simulation; and (d) CO$_2$+radiation driving factorial simulation. Positive values indicate increasing trends in the ratio and vice versa. All results from Mann-Kendall and Sen's slope statistical tests correspond to the 95% confidence interval.

Figure 9. Potential BVBC variation trend maps during the period of 1916 to 2015 under different factorial simulations. (a) CO2 driving factorial simulation; (b) CO2+precipitation driving factorial simulation. (c) CO2+temperature driving factorial simulation; and (d) CO2+radiation driving factorial simulation. Positive values indicate increasing trends in the ratio and vice versa. All results from Mann-Kendall and Sen's slope statistical tests correspond to the 95% confidence interval.
### 3.5 Constraints imposed by water limitations

Terrestrial water availability emerged as a key regulator of terrestrial carbon storage, by affecting the response mechanism of the vegetation carbon-stock to changes in driving factors (Fan et al., 2019; Humphrey et al., 2018; Ahlstrom et al., 2015; Madani et al., 2020; Humphrey et al., 2021; Ma et al., 2021). As shown in Figure 10, with an increase in the aridity index (i.e., an increase in available water), there is a gradually ascending trend in the enhanced magnitude and range in variation of AVBC density. Moreover, there is a link between fluctuations in the enhanced magnitude and range of variation in the BVBC density with the water stress gradient (Figure 11). These results suggest that water limitations lessen or even prevent carbon-stock fluctuations induced by changes in climate and CO2. To further investigate the controls of water limitation on the responses of inner carbon storages to each driver, we analyse the long-term variability of potential vegetation carbon-stocks by means of factorial simulations for each hydrological region (Figure 1). In factorial simulations, drivers attributed to increase AVBC density changed from $0.878 \pm 0.131$ kg C m$^{-2}$ in the hyper-arid regions to $5.459 \pm 0.610$ kg C m$^{-2}$ in the

Figure 10. Relationships in the incremental change between AI and AVBC over the hydrological regions. Modelled AVBC enhanced magnitude in the historical scenario S1 (a), CO2 in scenario S2 (b), precipitation in scenario S3 (c), temperature in scenario S4 (d), and radiation in scenario S5 (e). Range of the box is 25%-75% of values; range of the whiskers is 10%-90% of values; the small red square is average value; and the red line is the median line.
humid region during the past hundred years. Drivers attributed to increase BVBC density changed from 
0.011 ± 0.001 kg C m⁻² in the hyper-arid regions to 0.044 ± 0.005 kg C m⁻² in the humid regions during 
the same period (Figures A3, A4). With a lessening of water stress (from hyper-arid to humid area), the 
response of the carbon-stock to changes in climate and CO₂ gradually became more noticeable. The 
robust pattern in the regional average density of the carbon-stock shows that terrestrial water limitations 
strongly limit the enhanced magnitude of the carbon-stock.

Figure 11. Relationships in the incremental change in AI and BVBC over the hydrological 
regions. Modelled BVBC enhanced magnitude in the historical scenario S1 (a), CO₂ in scenario S2 
(b), precipitation in scenario S3 (c), temperature in scenario S4 (d), and radiation in scenario S5 (e). 
Range of the box is 25%-75% of values; range of the whiskers is 10%-90% of values; the small red 
square is average value; and the red line is the median line.

Water limitations not only directly reduced the magnitude of the increase in the two fractions' carbon-
stock (AVBC and BVBC) to changes in climate and CO₂, but also indirectly confined the response 
direction of each fractions' carbon-stock by transforming vegetation structure and function. Figure 12 
illustrates that spatial variations in the carbon-stock ratio within and between hydrological regions. Under 
the synergistic effect of drivers and water stress, vegetation carbon-stock increases, and there is a larger 
proportion of biomass allocated to, and stored in, aboveground vegetation organs. In drylands (AI≤0.5) 
of all factorial simulations, aboveground and belowground biomass carbon-stocks both increased but the
rate of change in the AVBC/BVBC ratio gradually decreased. Vegetation utilizes a tolerance strategy to allocate biomass, storing more biomass carbon in roots to resist enhanced water stress (Chen et al., 2013). In humid regions (AI>0.65), the proportion of AVBC increases more than that of BVBC to obtain more resources like CO₂ and radiation energy, leading to an increase in the AVBC/BVBC ratio. Conforming to the optimal partitioning hypothesis, plants store more carbon in shoots and leaves in environments where water is more available andshift more carbon to roots when water is more limited (Yang et al., 2010; Mcconnaughay and Coleman, 1999). Terrestrial water availability has a strong regulating effect on the spatial pattern of growth in the carbon-stock, demonstrating that the effects of the changes in climate and CO₂ on the dynamics of the vegetation carbon-stock are controlled by the terrestrial water gradient.

Figure 12. Temporal fluctuations in carbon-stock dynamics in vegetation biomass in different factorial simulations. Black indicates historical factorial simulation from 1901-2015, green indicates the CO₂-driven factorial simulation, blue indicates the precipitation-driven factorial simulation, red indicates the temperature-driving factorial simulation and yellow indicates radiation driven factorial simulation. Uncertainty bounds are provided as shaded areas reflect the intra-annual fluctuation (± 1 s.d.) (a) Modelled trend of AVBC/BVBC ratio in Global area. (b-f) Modelled trend of the AVBC/BVBC ratio in different hydrological regions.

4 Conclusions and discussions

To understand the response of carbon-sequestration potential and its inner biomass carbon-stocks to...
environmental change, we conducted a series of factorial simulations using SEIB-DGVM V3.02. More importantly, we investigated the extent of the responses of carbon-stocks to water limitations, and the correlation between terrestrial water and carbon flux.

Over the past 100 years, there has been an ongoing increase in the carbon storage capacity of the terrestrial ecosystem, which has slowed the rate at which atmospheric CO$_2$ has increased and may have mitigated global warming. These findings are consistent with the conclusions of research conducted at the local scale. For example, based on carbon flux data, Erb et al. (2008) suggested that the vegetation carbon-stock in Austria increased from 1043 Mt C to 1249 Mt C (AVBC growth was 1.059 Mt C yr$^{-1}$ and BVBC growth was 0.2 Mt C yr$^{-1}$) since industrialization. Le Noë et al. (2020) showed that increases in the carbon stocks and carbon density were the predominant drivers in the forest terrestrial carbon sequestration capacity in France from 1850 to 2015. Tong et al. (2020) also found a substantial increase of AVBC in southern China (0.11 Pg C yr$^{-1}$) during the period 2002–2017. However, these studies focused on regional trends in integral vegetation carbon-stocks and did not investigate the extent of the response in vegetation carbon-stocks partitioned between above- and belowground biomass. Our results show that the increase in carbon-stock in aboveground vegetation was much larger than that in belowground vegetation, and AVBC dominates the historical trend of the terrestrial carbon-stock. During the past decades, the global land surface has been greening because of the flux and storage of more carbon into plant trunks and foliage (Zhu et al., 2016). Based on our factorial simulations, the vegetation carbon-stock exhibited the most increase under the combined influence of CO$_2$ fertilization and temperature. In addition, the responses of carbon-stocks to other factors of change differed, particularly at the regional scale (Figure 7). Temporal AVBC and BVBC variations driven by precipitation and radiation were ultimately offset by compensatory effects, which dampened the long-term response of the carbon-stock to these factors. Our results revealed that trends in CO$_2$ and temperature drove historical long-term trends in the potential carbon-stocks, with faster increases and considerable variation occurring by region.

By partitioning the trends of AVBC and BVBC into five hydrological regions (Figure 1), we found that the long-term change in carbon-stocks is tightly coupled to terrestrial water availability. These results indicate that vegetation in humid regions is responsible for most of the trend in global AVBC, while
Plants in semi-arid regions play a dominate global role in controlling the long-term trend in BVBC. In addition, we demonstrated that water limitations controlled the terrestrial vegetation carbon-stocks (Ma et al., 2021). As water stress decreases, the magnitude and range in variation of carbon-stocks gradually increase (Figures 10, 11), which suggests that limited water availability constrains the response magnitude of the changes in carbon-stocks to changes in CO$_2$ and climate. In contrast, we found that indirect factors constrain the impact of increasing water stress on the response of carbon-stocks. Although vegetation carbon-stocks dramatically increase under the effects of climate and CO$_2$ changes, vegetation in humid regions stores more biomass (and carbon) in aboveground plant organs (trunk and foliage) to obtain nutrients and light. Dryland vegetation lowers the AVBC/BVBC ratios and stores more biomass below ground to enhance the capture of water resources. Terrestrial ecosystems utilize sensitive strategies to allocate and store biomass to adjust to local hydrological conditions, which is consistent with optimal partitioning theory (Mcconnaughay and Coleman, 1999). A significant conclusion is that water constraints not only confine the responses of vegetation carbon-stocks to drivers of variability, but also constrain the proportion of biomass carbon-stocks in above- and belowground fractions.

Distinguishing the response of carbon-stock fractions estimated by SEIB-DGVM improves the understanding of the interactive impacts of terrestrial carbon and water dynamics. However, uncertainty still exists because of the limitations in the processes of modelling vegetation metabolism with SEIB-DGVM. Trunk biomass contains tree branches and structural roots (coarse roots and tap roots) (Sato et al., 2007), so the R/S ratio of potential vegetation is smaller than the R/S of actual vegetation in factorial simulations. Fine root biomass is just a tiny fraction to the total biomass, but is has a very high turnover rate and determines the capacity of vegetation to absorb soil water. Availability of nitrogen is a key limiting factor for vegetation growth, especially when higher CO$_2$ fertilization effects exist (Tharammal et al., 2019). The limitation could be alleviated by nitrogen deposition in most temperate and boreal ecosystems. The SEIB-DGVM experiments were conducted with a focus on documenting CO$_2$ fertilization and climate change interactions; these experiments did not consider the influences of nitrogen deposition, which leads to a slight overestimate of the contributions of CO$_2$ fertilization on biomass production.
In summary, we evaluated SEIB-DGVM V3.02 and used this model to offer new perspectives on the response of vegetation carbon-sequestration potential to changes in climate and CO₂. Our simulation results show that changes in CO₂ rather than climate, dominate the above to belowground partitioning of the carbon-sequestration potential. More importantly, we suggest that the impact of CO₂ fertilization and temperature effects on vegetation carbon-sequestration potential depends on water availability and its impacts on plant stress. With increased global warming, water limitations are expected to increasingly confine global carbon-sequestration. Our findings highlight the need to account for terrestrial water limitation effects when estimating the response of the terrestrial carbon sequestration capacity to global climate change, and the need for stronger interactions between those involved in vegetation model development and those in between the hydrological and ecological research communities.
Appendices

Figure A1. Schematic of ecosystem carbon cycle. Yellow arrow indicates carbon flux. Atmospheric CO₂ transitions into gross primary production (GPP) by photosynthesis. GPP is partitioned into respiration and net primary production (NPP). NPP is partitioned into three biomass carbon pools (foliage, trunk, and root).

Figure A2. Land vegetation cover map from MCD12C1. END: Evergreen needleleaf forest, EBF: Evergreen broadleaf forest, DNF: Deciduous needleleaf forest, DBF: Deciduous broadleaf forest, MF: Mixed forest, CS: Closed shrublands, OS: Open shrublands, WS: Woody savannas, GL: Grasslands, NOV: No value.
Figure A3. Trends in average density of potential AVBC. (a) Modelled trend of annual averaged BVBC globally. Modelled trends in annual averaged AVBC in hyper-arid regions (b), arid regions (c), semi-arid regions (d), sub-humid regions (e), and humid regions (f).

Figure A4. Trends in average density of potential BVBC. (a) Modelled trend of annual averaged BVBC globally. Modelled trends in annual averaged BVBC in hyper-arid regions (b), arid regions (c), semi-arid regions (d), sub-humid regions (e), and humid regions (f).
semi-arid regions (d), sub-humid regions (e), and humid regions (f).

540 Code and data availability statement

541 The code of SEIB-DGVM version 3.02 can be download from http://seib-dgvm.com/. Climatic Research
542 Unit data can be downloaded from https://crudata.uea.ac.uk/cru/data/hrg/. The soil physical parameters
543 can be downloaded from www.iges.org/gswp. The reconstructed CO₂ concentration dataset and SEIB
544 code can be downloaded from http://seib-dgvm.com/. In model validation, Ecosystem Model-Data
545 Intercomparison (multiyear average NPP product) data were collected from
546 https://daac.ornl.gov/NPP/guides/NPP_EMDI.html. Remote sensing product MOD17A3 data were
547 obtained from https://lpdaac.usgs.gov/products/mod17a3hgf006/, and MCD12C1 data were obtained
548 from https://ladsweb.modaps.eosdis.nasa.gov/search/order.

549 Authors contributions

550 T.S. designed research. T.S., and S.H. performed research and developed the methodology. T.S. analyzed
551 data and produced the outputs. T.S., S.H., C.J., and X.C. wrote the first manuscript draft. W.W. and W.G.
552 supervised the study. All the authors discussed the methodology and commented on various versions of
553 the manuscript.

554 Competing interests

555 The authors declare that they have no conflict of interest.

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