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Historical and future quantification of terrestrial carbon sequestration from a Greenhouse-Gas-Value perspective

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ABSTRACT

Terrestrial ecosystems provide a range of important services to humans, including global and regional climate regulation. These services arise from natural ecosystem functioning as governed by drivers such as climate, atmospheric carbon dioxide mixing ratio, and land-use change. From the perspective of carbon sequestration, numerous studies have assessed trends and projections of the past and future terrestrial carbon cycle, but links to the ecosystem service concept have been hindered by the lack of appropriate quantitative service metrics. The recently introduced concept of the Greenhouse Gas Value (GHGV) accounts for the land-atmosphere exchanges of multiple greenhouse gases by taking into consideration the associated ecosystem pool sizes, annual exchange fluxes and probable effects of natural disturbance in a time-sensitive manner.

We use here GHGV as an indicator for the carbon sequestration aspects of the climate regulation ecosystem service, and quantify it at global scale using the LPJ-GUESS dynamic global vegetation model. The response of ecosystem dynamics and ecosystem state variables to trends in climate, atmospheric carbon dioxide levels and land use simulated by LPJ-GUESS are used to calculate the contribution of carbon dioxide to GHGV. We evaluate global variations in GHGV over historical periods and for future scenarios (1850–2100) on a biome basis following a high and a low emission scenario.

GHGV is found to vary substantially depending on the biogeochemical processes represented in LPJ-GUESS (e.g. carbon–nitrogen coupling, representation of land use). The consideration of disturbance events that occur as part of an ecosystem's natural dynamics is crucial for realistic GHGV assessments; their omission results in unrealistically high GHGV. By considering the biome-specific response to current climate and land use, and their projections for the future, we highlight the importance of all forest biomes for maintaining and increasing biogeochemical carbon sequestration. Under future climate and carbon dioxide levels following a high emission scenario GHGV values are projected to increase, especially so in tropical forests, but land-use change (e.g. deforestation) opposes this trend. The GHGV of ecosystems, especially when assessed over large areas, is an appropriate metric to assess the contribution of different greenhouse gases to climate and forms a basis for the monetary valuation of the climate regulation service ecosystems provide.

1. Introduction

The provision of terrestrial ecosystem services (ES, MEA, 2005; Haines-Yong and Potschin, 2013, for recent classification of ES) is variable in time and space, in response to changes in the environment such as climate warming and land-use/land-cover changes (LULCC). Expecting that anthropogenic pressures on terrestrial resources will continue to grow over the coming decades, it is becoming increasingly important to understand the regionally disparate behavior of ES and their transition over time. In this context, one globally relevant ecosystem service that is strongly modified by human-induced environmental changes is climate regulation, especially the ability of the biosphere to either sequester or emit greenhouse gases (GHG) (MEA, 2005). The exchange of GHGs between the ecosystem and the atmosphere is usually quantified by accounting for changes in the organic matter stored in an ecosystem (e.g. REDD+, see Miles and Kapos, 2008; UNFCCC, 2008), the flux of GHG to or from the atmosphere (e.g. CCX, 2009; Lal, 2004), or a combination of both (e.g. IPCC, 2006; see Anderson-Teixeira and DeLucia, 2011, for an extensive summary). However, each of these methods neglects one or more aspects of

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system behavior, and thus fails to account for all of the contributions of ecosystems to regional and global climate.

The Greenhouse Gas Value (GHGV) of ecosystems, a comprehensive method to quantify the contribution of terrestrial ecosystems to biogeochemical aspects of climate regulation was recently introduced by Anderson-Teixeira and DeLucia (2011, abbreviated AT&D11 henceforth). GHGV assesses the value of maintaining an ecosystem over a multi-year time frame by calculating the change in GHG-induced radiative forcing that would result from the clearing of 1 ha of the ecosystem. The method considers multiple GHGs released through oxidation of stored organic material upon clearing of the ecosystem, as well as the displaced annual GHG flux, including the probable effects of large natural disturbances in the ecosystem. The GHGV of an ecosystem thus is not only determined by high organic matter storage that would be released upon clearance, the value is enhanced if that ecosystem would have continued to take up carbon if it had not been cleared, and if at the same time the probability of being severely affected by natural disturbances (e.g. fire, insect attack, wind-throw) over the assessment period is low. The contributions from storage, annual flux, and the effects of disturbance, are expressed relative to the radiative forcing of a pulse CO_2 emission, with GHGV being expressed in Mg CO_2-equiv. ha^{-1}.

An observation-based estimation of ecosystem GHGV (e.g. AT&D11; Anderson-Teixeira et al., 2012) is limited by data availability and quality. It is particularly problematic in regions where observations are rare. In addition, estimates of GHGV scaled up from plot studies are likely to miss or under-sample the effects of large, infrequent disturbances, thereby overestimating both stored organic material and ongoing uptake of carbon. Here we use a dynamic global vegetation model (DGVM) to enable global-scale calculation of GHGV and its evolution over time. With a DGVM, the GHGV is derived as a direct result of simulated ecosystem dynamics including disturbances, and changes in GHGV are intrinsically linked to individual biogeochemical processes and environmental and/or anthropogenic drivers. Applying a DGVM allows consideration of how past or future environmental changes affect GHGVs through their effects on ecosystem function. We concentrate here on the carbon sequestration aspects of GHGV (GHGV of CO_2) for ecosystems in their potential natural state without and with accounting for interactions of carbon (C) and nitrogen (N) cycles, and under the consideration of agricultural land-use. We assess in particular how GHGV varies spatially and through time in response to changes in climate, atmospheric CO_2 mixing ratio and land-use. We cover in our analysis variations over historical periods (beginning in 1850) and a range of future scenarios (until 2100) under a high (RCP 8.5) and a low (RCP 2.6) emission scenario.

2. Methods

2.1. LPJ-GUESS DGVM

LPJ-GUESS DGVM (Smith et al., 2001, 2014; Sitch et al., 2003) is a process-based model that simulates vegetation dynamics and biogeochemical cycles as a function of prevailing climate, soil type and atmospheric CO_2 mixing ratio (Fig. 1). Potential natural vegetation is modeled by 11 tree and grass plant functional types (PFT; Table S1), which differ in aspects such as photosynthetic pathway, optimum temperature range for photosynthesis, and phenology. Competition for resources and light among age cohorts of woody plant individuals in natural vegetation is simulated directly through gap dynamics (see, e.g. Bugmann, 2001). Vegetation establishment and mortality are treated stochastically across a number of replicate (here: 10) patches, representative for an area of ca. 1000 m^2, that are averaged to form a representative sample of vegetation within a grid cell. The model has been evaluated extensively and has demonstrated skill in capturing large-scale vegetation patterns (Hickler et al., 2006, 2012) and dynamics of the terrestrial carbon cycle (Ahlström et al., 2012; Morales et al., 2005; Piao et al., 2013). The carbon flux response was shown to be close to the ensemble mean in a recent intercomparison of nine dynamic global vegetation models (Sitch et al., 2013).

In addition to the base version (PNV), two recent developments of the LPJ-GUESS model are used here to include the effects of accounting for additional ecosystem processes and nutrient cycles.

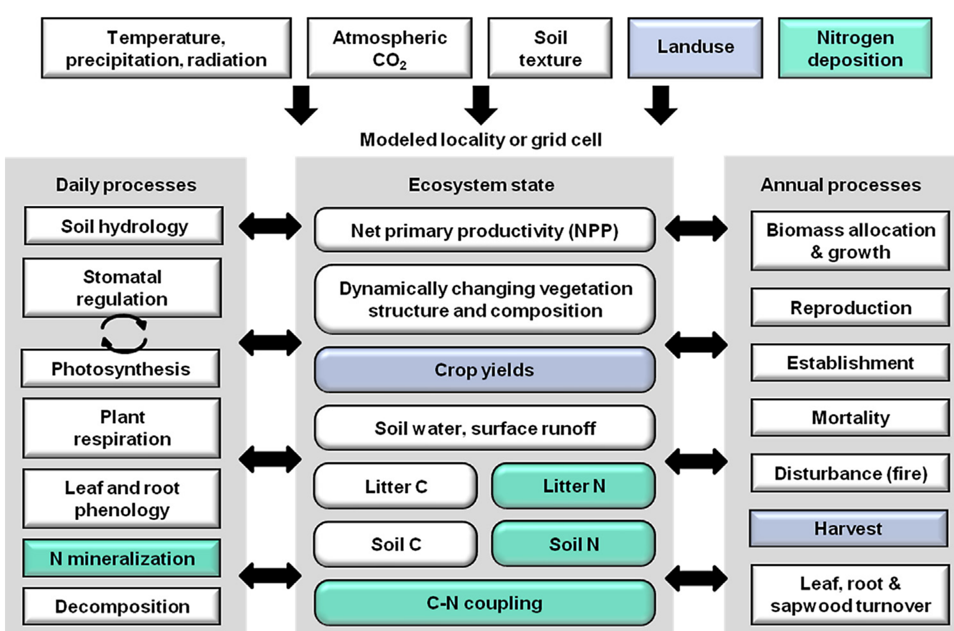

Fig. 1. Major processes within LPJ-GUESS DGVM for the base version simulating potential natural vegetation, and including additional features for considering carbon–nitrogen dynamics (highlighted in green, version PNV_N) and representing cropland and land-use changes (highlighted in blue, version CLU) (after Smith et al., 2001). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)