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Contribution of forests to the carbon sink via biologically-mediated silicate weathering: A case study of China

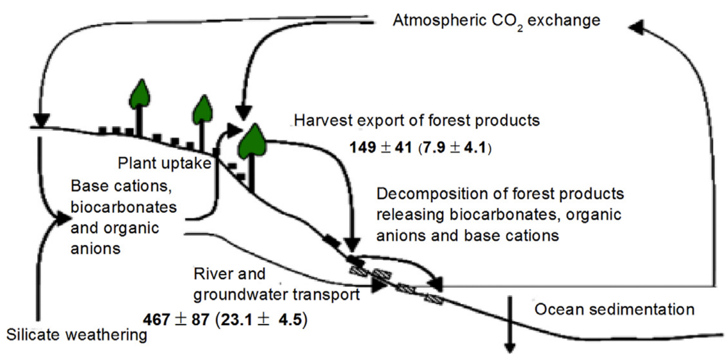
Zhaoliang Song [a,*], Hongyan Liu [b,*], Caroline A.E. Strömberg [c,*], Hailong Wang [d], Peter James Strong [e], Xiaomin Yang [a], Yuntao Wu [a]

[a] Institute of the Surface-Earth System Science Research, Tianjin University, Tianjin 300072, China
[b] College of Urban and Environmental Sciences, Peking University, Peking 100871, China
[c] Department of Biology, Burke Museum of Natural History and Culture, University of Washington, Seattle, WA 98195, USA
[d] School of Environmental and Chemical Engineering, Foshan University, Foshan, Guangdong 528000, China
[e] School of Chemistry, Physics and Mechanical Engineering, Queensland University of Technology, GPO Box 2432, 2 George St, Brisbane, QLD 4001, Australia

HIGHLIGHTS

- Atmospheric CO_2 sequestration through weathering is a stable carbon sink.
- Plants biologically enhance weathering-related CO_2 consumption.
- Biomass-related silicate weathering in China may consume 7.9 ± 4.1 Tg CO_2 yr^{-1}.
- Forests may increase CO_2 sequestration through silicate weathering by ~32%.

GRAPHICAL ABSTRACT



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ABSTRACT

During silicate weathering, atmospheric carbon dioxide (CO_2) is consumed and base cations are released from silicate minerals to form carbonate and bicarbonate ions, which are finally deposited as carbonate complexes. Continental silicate weathering constitutes a stable carbon sink that is an important influence on long-term climate change, as it sequesters atmospheric carbon dioxide at a million-year time scale. Traditionally, CO_2 sequestered through silicate weathering is estimated by measuring the flux of the base cations to watersheds. However, plants also absorb considerable amounts of base cations. Plant biomass is often removed from ecosystems during harvesting. The base cations are subsequently released after decomposition of the harvested plant materials, and thereby enhance CO_2 consumption related to weathering. Here, we analyze plant biomass storage-harvest fluxes (production and removal of biomass from forests) of base cations in forests across China to quantify the relative contribution of forest trees to the terrestrial weathering-related carbon sink. Our data suggest that the potential CO_2 consumption rate for biomass-related silicate weathering (from the combined action of with afforestation/reforestation, controlled harvesting and rock powder amendment) in Chinese forests is 7.9 ± 4.1 Tg CO_2 yr^{-1}. This represents ~34% of the chemical weathering rate in China. Globally, forests may increase CO_2 sequestration through biologically-mediated silicate weathering by ~32%.

* Corresponding authors at: Institute of the Surface-Earth System Science Research, Tianjin University, NO. 92, Weijin Road, Tianjin 300072, China.
E-mail addresses: zhaoliang.song@tju.edu.cn (Z. Song), lhy@urban.pku.edu.cn (H. Liu), caestrom@u.washington.edu (C.A.E. Strömberg).

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1. Introduction

During silicate weathering, atmospheric carbon dioxide (CO_2) is consumed and base cations are released from silicate minerals to form carbonate and bicarbonate ions, which are finally deposited within soil profiles or transported to a lake or marine environment and precipitated as carbonate complexes (Gaillardet et al., 1999; Amiotte-Suchet et al., 2003; Song et al., 2012). Each year, the chemical weathering of continental silicates consumes 380 to 553 Mt (or Tg) of atmospheric carbon dioxide globally (Meybeck, 1987; Gaillardet et al., 1999). Despite this major contribution to the global carbon sink, the role of chemical weathering in the terrestrial carbon balance and in climate change has until recently only been considered in studies dealing with geological time scales as it was thought to be a relatively slow process (e.g. Berner, 1997; Gaillardet et al., 1999; Hagedorn and Cartwright, 2009; Maher and Chamberlain, 2014). However, recent data analyses and modeling have indicated (1) that continental silicate weathering flux responds to 10 to 100 year-scale climate change (Gislason et al., 2009; Beaulieu et al., 2012), and (2) that the flux may be greatly accelerated by rapid erosion (Larsen et al., 2014), the addition of pulverized silicate rocks to soils and sea (Schuiling and Krijgsman, 2006; Köhler et al., 2010; Cressey, 2014; Moosdorf et al., 2014; Taylor et al., 2016), or terrestrial plant growth (Berner, 1997; Moulton et al., 2000; Song et al., 2011; Manning and Renforth, 2012). As an example of the latter, the sequestration flux of atmospheric CO_2 through weathering of Icelandic basalts correlates directly with wetland coverage and net primary production (NPP) (Kardjilov et al., 2006).

In addition to acid generation to release nutrients for biomass generation and microbial-induced chelation (Drever, 1994; Taylor et al., 2009; Manning and Renforth, 2012; Manning et al., 2013), an important mechanism underlying the silicate weathering caused by plants is the rapid uptake of base cations and silicon during plant growth and harvest (Balogh-Brunstad et al., 2008). This removal destabilizes silicate minerals (Bormann et al., 1998; Song et al., 2012; Vadeboncoeur et al., 2014). It has recently been estimated that changes in silica (SiO_2), potassium (K), sodium (Na), calcium (Ca) and magnesium (Mg) uptake by terrestrial vegetation may significantly affect silicate weathering on time scales as short as 100 to 1000 years (Street-Perrott and Barker, 2008; Uhlig et al., 2017). The effect of plants on continental silicate weathering caused by nutrient uptake varies greatly among different vegetation types (Street-Perrott and Barker, 2008; Song et al., 2011, 2012) and is influenced by growth phases of vegetation and the timing of harvest (Balogh-Brunstad et al., 2008). Generally, the nutrient uptake effect of forests on weathering is thought to surpass that of other terrestrial ecosystems (e.g. grasslands, wetlands and croplands) due to a greater plant biomass storage-harvest flux (the flux in kg ha^{-1} yr^{-1}) and lower fluxes of fertilizer application (Street-Perrott and Barker, 2008; Song et al., 2011).

Both carbon and base cations are sequestered during wood production and released after wood degradation/oxidation (Bormann et al., 1998; Vadeboncoeur et al., 2014). A significant amount of base cations absorbed by forest plants is removed from forests during biomass harvesting. These are often released elsewhere after decomposition of the harvested forest products, although the release time of cations from lumber products depends on the processing and use of the timber (Bormann et al., 1998; Sverdrup and Rosen, 1998; Vadeboncoeur et al., 2014). Base cations and bicarbonates derived from direct silicate weathering (Gaillardet et al., 1999; Amiotte-Suchet et al., 2003; Song et al., 2012) and released from decomposed forest material may finally be deposited at the bottom of a soil profile, or transported to a lake or marine environment and precipitated as carbonates. Therefore, forest plant growth and harvesting may enhance biological weathering-related CO_2 consumption (Song et al., 2012). However, the precise contribution made by forests to the continental silicate weathering carbon sink has not been quantified at a regional or a global scale.

Here, we evaluate the impact of forests on rates of continental-weathering related carbon sequestration using China as a case study. China accounts for 6% of the global CO_2 consumption rate related to weathering (Qiu et al., 2004; Wu et al., 2011) and has $>140 \times 10^6$ ha of forests growing on soils dominated by silicate minerals. Most of the forests in China are distributed in subtropical and temperate hilly or mountainous areas - with sufficient primary silicate mineral generated from soil erosion and disturbed by human activities such as harvesting (Fang et al., 2001; FAO, 2010). Although repeated intensive forest harvesting may finally exhaust soil base cation pool as a result of biomass harvest removal and base cation leaching loss (Lucas et al., 2014), we hypothesize that combination with other measures such as silicate rock powder amendment in some forest regions with extremely acidic soils, sustainable harvest of forests such as those in China can accelerate silicate weathering and supply base cations for forest regeneration (Bormann et al., 1998; Vadeboncoeur et al., 2014). We use the mass balance calculation method based on data of forest area, average cation contents of trees weighted by tissue biomass, and NPP of forests (Materials and methods section) to compare CO_2 consumption flux and rates of biomass-related silicate weathering among different forest types and to investigate the contribution of forests to carbon sink through continental silicate weathering.

2. Materials and methods

2.1. General characteristics of the Chinese forests

Chinese forests range from tropical forests in the south to boreal forests in the north. To better understand the silicate weathering carbon sink in Chinese forests, we divided Chinese forests developed on soils dominated by silicate minerals into seven forest types based on climatic conditions and physiology: tropical (T) forest, subtropical and tropical bamboo (STB) forest, subtropical evergreen broad-leaf and mixed (SEBM) forest, subtropical and tropical coniferous (STC) forest, temperate deciduous broad-leaf (TDB) forest, coniferous and broad-leaf mixed

Table 1
Characteristics of the seven Chinese forest types (Hou, 1982; Song et al., 2013).

Forest type[a]	Area (10^6 ha)	MAP (mm)[b]	MAT (°C)[c]	Forest subtype
T	0.95	1600–2000	21–26	Semi-deciduous monsoon forest, Montane rainforest
STB	7.2	1000–2000	14–26	*Phyllostachys pubescens* forest, *Phyllostachys violascens* forest
SEBM	33.9	800–1600	16–20	*Castanopsis* forest, *Pinus-Castanopsis* mixed forest, *Lithocarpus xylocarpus* forest
STC	29.5	800–1600	8–20	*Cunninghamia lanceolata* forest, *Cathaya argyrophylla* forest, *Pinus massoniana* forest, *Pinus armandii* forest
TDB	42.4	500–1000	8–20	*Quercus variabilis* forest, *Quercus liaotungensis* forest, *Quercus mongolica* forest, *Betula platyphylla* forest
CB	4.7	500–1600	2–14	*Pinus-Quercus* mixed forest, Broad leaf tree-*Pinus* mixed forest
CTC	24.1	400–600	−6–8	*Pinus tabulaeformis* forest, *Platycladus orientalis* forest, *Pinus koraiensis* forest, *Pinus sylvestris* var.*mongolica* forest, *Larix gmelinii* forest

[a] T, tropical forest; STB, subtropical and tropical bamboo forest, SEBM, subtropical evergreen broad-leaf and mixed forest; STC, subtropical and tropical coniferous forest; TDB, temperate deciduous broad-leaf forest; CB, coniferous and broad-leaf mixed forest; CTC, cold-temperate and temperate coniferous forest.
[b] MAP, mean annual precipitation.
[c] MAT, mean annual temperature.