ECOLOGY

Four decades of data indicate that planted mangroves stored up to 75% of the carbon stocks found in intact mature stands

Carine F. Bourgeois[1]†, Richard A. MacKenzie[1]*†, Sahadev Sharma[2]†, Rupesh K. Bhomia[3]†, Nels G. Johnson[4]†, Andre S. Rovai[5,6], Thomas A. Worthington[7], Ken W. Krauss[8], Kangkuso Analuddin[9], Jacob J. Bukoski[10], Jose Alan Castillo[11], Angie Elwin[12], Leah Glass[13], Tim C. Jennerjahn[14,15], Mwita M. Mangora[16], Cyril Marchand[17], Michael J. Osland[8], Ismaël A. Ratefinjanahary[12], Raghab Ray[18], Severino G. Salmo III[19], Sigit D. Sasmito[20], Rempei Suwa[21], Pham Hong Tinh[22], Carl C. Trettin[23]

Mangroves' ability to store carbon (C) has long been recognized, but little is known about whether planted mangroves can store C as efficiently as naturally established (i.e., intact) stands and in which time frame. Through Bayesian logistic models compiled from 40 years of data and built from 684 planted mangrove stands worldwide, we found that biomass C stock culminated at 71 to 73% to that of intact stands ~20 years after planting. Furthermore, prioritizing mixed-species planting including *Rhizophora* spp. would maximize C accumulation within the biomass compared to monospecific planting. Despite a 25% increase in the first 5 years following planting, no notable change was observed in the soil C stocks thereafter, which remains at a constant value of 75% to that of intact soil C stock, suggesting that planting effectively prevents further C losses due to land use change. These results have strong implications for mangrove restoration planning and serve as a baseline for future C buildup assessments.

INTRODUCTION

In conjunction with historical losses, an estimated 35% of global mangrove area has been lost over the past five decades to human-driven land-use change, extreme weather events, and erosion (*1*–*3*). However, growing awareness around mangrove-dependent socio-ecological well-being has led to important conservation and restoration efforts of these ecosystems, with annual deforestation rates declining from 0.7 to 1% in the 1980s to 1990s to 0.2 to 0.4% in the early 2000s (*1*, *4*). Because mangroves have one of the highest net ecosystem productivity rates and carbon (C) storage potential on the globe (*5*–*7*), restoring or rehabilitating these ecosystems has been regarded as a promising long-term nature-based solution to partly offset emissions of greenhouse gases (GHGs) while simultaneously enhancing biodiversity and contributing to coastal protection (*8*, *9*).

Although research is increasingly highlighting the greater suitability of (assisted) natural regeneration and hydrological restoration, planting remains the predominant mangrove restoration and rehabilitation strategy, despite the fact that many planting attempts fail, largely due to planting species in unsuitable biophysical conditions (*10*, *11*). Despite the perceived benefit of restoration, there is now no consensus on the timeline required for successful planted mangrove stands to recover or build up levels of C stocks similar to natural mangrove forests, with alluded periods ranging anywhere from 20 to 50 years (*12*–*18*) to over a century (*19*). As the United Nation (UN) general assembly has declared 2021 to 2030 as the UN Decade on Ecosystem Restoration (*20*), mangrove restorable area is estimated at 8120 km^2, of which 6665 km^2 are considered to be highly restorable (*21*). Understanding how effective past mangrove restoration projects have been at returning antecedent C stocks across different locations and species composition is therefore critical in prioritizing future efforts and maximizing success in these restorable areas.

Here, we assessed whether mangrove planted stands demonstrate similar ability to store C as natural primary stands including primary forests including intact forest landscapes (PF-IFL), i.e., free of notable human degradation (*22*), hereafter called "intact," as well as within which timelines. Briefly, we collected 40 years of data on C stocks in planted stands, including in restored/rehabilitated (i.e., where

[1]Institute of Pacific Islands Forestry, Pacific Southwest Research Station, USDA Forest Service, Hilo, HI 96720, USA. [2]Institute of Ocean and Earth Sciences, University of Malaya, Kuala Lumpur 50603, Malaysia. [3]Center for International Forestry Research (CIFOR), International Centre for Research in Agroforestry (ICRAF); D. P. Wijesinghe Mawatha, Battaramulla, Colombo, Sri Lanka. [4]Institute of Pacific Islands Forestry, Pacific Southwest Research Station, USDA Forest Service, Albany, CA 94710, USA. [5]US Army Engineer Research and Development Center, Vicksburg, MS 30180, USA. [6]Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, USA. [7]Conservation Science Group, Department of Zoology, University of Cambridge, Cambridge CB2 3QZ, UK. [8]US Geological Survey, Wetland and Aquatic Research Center, Lafayette, LA 70506, USA. [9]Biotechnology Program, Mathematics and Natural Sciences, Universitas Halu Oleo, Kendari, Southeast Sulawesi 93232, Indonesia. [10]Department of Forest Ecosystems and Society, College of Forestry, Oregon State University, Corvallis, OR 97331, USA. [11]Ecosystems Research and Development Bureau, Department of Environment and Natural Resources, Forestry Campus, Los Baños 4031, Philippines. [12]Department of Geography and Environmental Science, University of Reading, Reading RG6 6AB, UK. [13]Blue Ventures Conservation, Antananarivo 101, Madagascar. [14]Leibniz Centre for Tropical Marine Research, Bremen 28359, Germany. [15]Faculty of Geosciences, University of Bremen, Bremen 28359, Germany. [16]Institute of Marine Sciences, University of Dar es Salaam, Buyu Campus, Zanzibar P.O. Box 668, Tanzania. [17]ISEA, Université de la Nouvelle-Calédonie, Nouméa, New Caledonia 98851, France. [18]Atmosphere and Ocean Research Institute, The University of Tokyo, Kashiwa 277-8564, Japan. [19]Institute of Biology, College of Science, University of the Philippines Diliman, Quezon City 1101 Philippines. [20]NUS Environmental Research Institute, National University of Singapore, Singapore 117411, Singapore. [21]Japan International Research Center for Agricultural Sciences (JIRCAS), Tsukuba 305-8686, Japan. [22]Faculty of Environment, Hanoi University of Natural Resources and Environment, Hanoi 10000, Vietnam. [23]Center for Forested Wetlands Research, Southern Research Station, USDA Forest Service, Cordesville, SC 29434, USA.
*Corresponding author. Email: richard.mackenzie@usda.gov
†These authors contributed equally to this work.