應用高密度土壤採樣與克利金法提升紅樹林土壤碳庫估算之空間代表性

Enhancing the Spatial Representativeness of Mangrove Soil Carbon Stock Estimates Using High-Density Soil Sampling and Kriging Method

國立臺灣大學生物環境系統工程學系

研究助理 黃仁愉 Ooi Ren Yi

副教授 蕭友晉 Yo-Jin Shiau

摘　要

紅樹林土壤碳是藍碳生態系統中最主要且穩定的碳庫，佔整體碳儲存比例可達 50–90%。然而，由於紅樹林地形複雜、受潮汐影響且採樣成本高昂，傳統的土壤碳監測多仰賴少量樣點進行平均值估算，並將其乘以整體面積以推算土壤碳庫總量。此種作法未能考慮紅樹林土壤碳的空間異質性，尤其在受人為干擾或地形變異大等影響的地區，可能導致顯著低估或高估。針對紅樹林土壤碳的空間變異特性與樣點數設計，相關研究仍相對有限。本研究以臺灣三處紅樹林地區，關渡、塭子頭與芳苑為研究對象，針對每一區域分別進行約 50–60 個點的高密度土壤碳採樣，作為空間統計分析之基礎。研究目的是透過密集實測資料，建立可靠的土壤碳空間分布圖，並探索不同紅樹林地區的碳異質性表現。資料處理上，先進行經驗變異數分析，並套用普通克利金法進行空間推估。本研究比較了三種常用變異數模型（spherical、exponential、gaussian），並以 RMSE 為評估標準挑選最佳模型與參數組合，並視覺化產出每區的土壤碳推估圖與不確定性圖層（MSE、RMSE）。 目前分析結果顯示，不同地區的土壤碳分布具明顯空間異質性，各地最佳模型與參數差異顯著，證實無法使用統一模型進行全區推估，需依地區特性個別建模。本研究建立一套臺灣本土小尺度空間建模之操作流程，並可作為後續進行樣點減量分析與監測成本效益評估的基礎。整體而言，本研究有助於補足目前藍碳研究中缺乏樣點數與空間代表性之間量化依據的空白，並為建立本土化紅樹林碳匯監測提供方法學參考。

關鍵詞：紅樹林土壤碳，普通克利金法，空間分析

Abstract

Mangrove soil organic carbon (SOC) is one of the most significant and stable carbon reservoirs within blue carbon ecosystems, accounting for approximately 50–90% of the total carbon stock. However, due to the complex terrain, tidal influence, and high cost of field sampling in mangrove environments, conventional monitoring approaches often rely on a small number of sampling points (e.g., 3–10) to estimate mean carbon density, which is then multiplied by the total area to infer carbon stocks. This method does not account for the spatial heterogeneity of SOC, especially in areas with significant anthropogenic disturbance or microtopographic variation, potentially leading to substantial under- or overestimation. Despite this, research focusing on the spatial variability of SOC in mangroves and corresponding sampling design remains relatively limited. This study focuses on three mangrove areas in Taiwan (Guandu, Wenzitou, and Fangyuan) where approximately 50 to 60 high-density soil samples were collected per site to serve as a basis for spatial statistical analysis. The objective was to construct reliable SOC spatial distribution maps using dense empirical data and to explore differences in spatial heterogeneity across different mangrove regions. We conducted empirical variogram fitting and applied ordinary kriging to estimate spatial distributions. Three commonly used variogram models (spherical, exponential, and gaussian) were compared, and the best-fitting model and parameter combination for each site was selected based on root mean square error (RMSE). SOC prediction maps and uncertainty maps (MSE, RMSE) were generated accordingly. The results indicate clear spatial heterogeneity in SOC across different sites, with notable differences in optimal models and parameters among regions. This suggests that a unified model is not suitable for all areas, and site-specific modeling is necessary. This study establishes a practical workflow for small-scale spatial modeling of mangrove SOC in Taiwan and lays the groundwork for future analyses such as sampling optimization and cost-effectiveness assessment. Overall, the study contributes to addressing the current gap in blue carbon monitoring regarding the quantitative relationship between sample size and spatial representativeness and offers methodological references for developing localized mangrove carbon monitoring strategies.

Keywords: mangrove soil carbon, ordinary kriging, spatial analysis