SWAT+與 InVEST 模式應用於集水區生態系統服務之碳儲存評估

Assessing Carbon Storage of Watershed Ecosystem Services by Employing The SWAT+ and InVEST Models

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摘　要

全球氣候變遷是當今世界面臨最嚴峻的環境挑戰之一，氣候變遷包括氣溫升高、降水分布變化、極端氣候事件頻發以及海平面上升等等，這些變遷對整個人類永續發展及福祉帶來了多方面的影響以及壓力。

在 2015 年，聯合國宣布了「2030 永續發展目標」(Sustainable Development Goals, SDGs)，其中提到減緩及調適行動，以因應氣候變遷之影響；加強保育及永續利用陸域生態系，確保生物多樣性並防止土地劣化等，而人類活動所造成之氣候變遷對生態系統生物以及環境多樣性有著嚴重的影響，導致地球的環境恢復力和生物承載量都明顯減少。聯合國於 2001 年啟動了一項全球性研究計劃，旨在評估生態系統變化對人類福祉的影響，並發布了《千禧年生態系統評估》報告書，將生態系統服務分成四大服務項目：支持、供給、調節以及文化服務，其中調節服務提到氣候變遷，大氣中二氧化碳濃度不斷因人為活動而持續升高，因此生態系統服務中將碳吸存服務歸類於調節服務之重要服務。

本研究所使用之評估模式為 SWAT+(Soil and Water Assessment Tool+)與 InVEST(Integrated Valuation of Ecosystem Services and Tradeoffs)模式，SWAT(SWAT+)模式已在多篇研究中顯示其評估生態系統服務之能力，因其詳細的水文模擬過程及檢定驗證之功能使其模擬之結果較為準確可信，以提供決策者未來面對氣候變遷、極端降雨、農作物產量、肥料施肥等制定政策方向，多數研究集中於美國和中國，主要評估的生態系統服務類型包括水供給(Water supply)、水質淨化(Water purification)、食物生產(Crop production)、土壤保持(Soil conservation)、氮和磷的保持(Nitrogen & phosphorus retention)等；InVEST 模式則為專門用於生態系統服務的模式，其優勢為操作簡便，計算生態系統服務方法上較為簡化，輸入數據量需求較低。目前依地球生態系型態分布之淡水、海洋、陸地以及其他生態系統等，共有 25 種生態系服務效益計算模式。

本研究旨在應用 SWAT+與 InVEST 模式於水庫集水區之碳儲存服務評估，以瞭解研究區域碳儲存之概況。本文研究區域位於台灣新北市之翡翠水庫集水區，該區有大量林木所組成之森林資源，對於固定大氣碳素、降低大氣中二氧化碳排放之調節服務功能提供一個重要角色及場域。研究內容主要是應用 SWAT+模式模擬集水區的陸域生態系統，包含水文系統、輸砂、營養鹽循環，以及植物之生長模擬，以計算生態系統之生物量再結合 InVEST 模式以推估集水區之碳儲存概況，最後探討 SWAT+模式與 InVEST 模式使用碳儲存服務功能指標對於碳儲存的模擬之差異以及關聯性。

在 SWAT+模式模擬方面，本研究收集 2008 年至 2021 年共 14 年氣象、地文和水文資料，對坪林站之流量、輸砂量及營養鹽進行模式參數的檢定驗證；其中 2008 年設定為暖身期，2009 年至 2015 年共 7 年實測資料進行檢定，2016 年至 2021 年共 6 年實測資料進行驗證模擬結果。以下研究結果均以坪林站資料與月模擬作檢定驗證，研究結果顯示流量檢定與驗證效率係數均達到 0.8 以上；泥砂之檢定效率係數達到 0.841，驗證之結果也達到 0.685；在營養鹽模擬上也呈現合理結果，氨氮檢定與驗證效率係數均達到 0.7 以上；硝酸鹽氮檢定與驗證效率係數均達到 0.6 以上；有機氮檢定效率係數為 0.609，驗證為 0.459；總氮檢定效率係數達到 0.693，驗證達到 0.569。正磷酸鹽檢定效率係數為 0.758，驗證為 0.575，總磷檢定與驗證效率係數均達到 0.6 以上。綜合上述模擬結果顯示 SWAT+模式對翡翠水庫集水區長期的水文以及營養鹽模擬結果相當良好。在碳儲存碳庫估算方面，SWAT+ 模式計算得陸域上的為森林、作物等生物量以及土壤有機碳，因此生物量需透過乘以碳含量百分比轉換後方可計算固碳量，最後 SWAT+模式模擬出之翡翠水庫集水區年平均碳儲存量約為 411.73 噸/公頃，年平均生物量約為 282.48 噸/公頃，符合 IPCC 2006 指南的林地生物量範圍，顯示 SWAT+模式對翡翠水庫集水區陸域植物生物量之模擬相當合理。

在 InVEST 模式模擬方面，本研究參考 InVEST 模式手冊，並查閱聯合國政府間氣候變化專門委員會(Intergovernmental Panel on Climate Change ,IPCC)國家溫室氣體清冊告 2006 年之單位固碳量，包含地上部、地下部、土壤以及枯有機質之單位固碳量，再進行套圖分析年平均之碳儲存碳庫量，計算出翡翠水庫集水區年平均碳儲存量約為 333.7 噸/公頃。

綜合 SWAT+模式與 InVEST 模式之結果比較，InVEST 模式的輸入參考值，是屬於大尺度、地區性的範圍，例如:熱帶、副熱帶森林等大規模區域之森林作為一個參考範圍，但對於某特定區域小尺度之集水區來說，要掌握較符合區域特性的輸入就存在著較大的不確定性，但其優勢是快速有效率的評估；SWAT+模式的模擬則可藉由實測值，透過參數檢定驗證過程，使得模擬值能提供更高的可信度，但其缺點是集水區各種歷程相當複雜耗時，計算也需處理大量的數據。

關鍵詞：SWAT+，InVEST，生態系統服務，碳儲存

Abstract

Global climate change is one of the most severe environmental challenges facing the world today. Climate change encompasses rising temperatures, altered precipitation patterns, frequent extreme weather events, and rising sea levels. These changes impose multifaceted

impacts and pressures on sustainable development and human well-being.

In 2015, the United Nations announced the "2030 Sustainable Development Goals" (SDGs), which emphasize mitigation and adaptation actions to address the effects of climate change; enhancing the conservation and sustainable use of terrestrial ecosystems, ensuring biodiversity, and preventing land degradation. Climate change induced by human activities has a severe impact on ecosystems and environmental diversity, significantly reducing the Earth's resilience and biological carrying capacity. In 2001, the United Nations launched a global research initiative aimed at assessing the impact of ecosystem changes on human well-being and published the Millennium Ecosystem Assessment report. This report categorized ecosystem services into four major categories: supporting, provisioning, regulating, and cultural services. Among these, regulating services include climate change, with rising atmospheric carbon dioxide concentrations due to human activities, categorizing carbon sequestration as an essential service within regulating services.

This study employs the SWAT+ (Soil and Water Assessment Tool+) and InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) models. The SWAT (SWAT+) model has demonstrated its ability to assess ecosystem services in numerous studies, owing to its detailed hydrological simulation processes and validation functions, which ensure more accurate and reliable simulation results. These results can provide policymakers with guidance on addressing climate change, extreme rainfall, crop yields, fertilizer application, and other issues. Most studies have focused on the United States and China, primarily evaluating ecosystem services such as water supply, water purification, crop production, soil conservation, and nitrogen and phosphorus retention. The InVEST model is specifically designed for ecosystem services, offering advantages of simplicity in operation, simplified methods for calculating ecosystem services, and lower input data requirements. Currently, there are 25 ecosystem service benefit calculation models based on the distribution of Earth's ecological types, including freshwater, marine, terrestrial, and other ecosystems.

This study aims to apply the SWAT+ and InVEST models to assess carbon storage services in a reservoir watershed to understand the carbon storage status in the study area. The study area is located in the Feitsui Reservoir watershed in New Taipei City, Taiwan. This area comprises abundant forest resources, playing a vital role and serving as a field for atmospheric carbon fixation and reducing atmospheric carbon dioxide emissions through its regulating services. The study primarily applies the SWAT+ model to simulate the terrestrial ecosystem in the watershed, including hydrological systems, sediment transport, nutrient cycling, and plant growth simulations to calculate biomass. The InVEST model is then combined to estimate the carbon storage status in the watershed. Finally, the study explores the differences and correlations between the SWAT+ and InVEST models in using carbon storage service function indicators for carbon storage simulation.

In the SWAT+ model simulation, this study collected 14 years of meteorological, topographical, and hydrological data from 2008 to 2021 to calibrate and validate model

parameters for flow, sediment transport, and nutrients at the Pinglin Station. The year 2008 was set as the warm-up period, with 7 years of observed data from 2009 to 2015 used for calibration and 6 years of observed data from 2016 to 2021 used for validation. The calibration and validation of monthly simulations were performed using data from the Pinglin Station. The results showed that the efficiency coefficients for flow calibration and validation were both above 0.8; for sediment, the calibration efficiency coefficient reached 0.841, and the validation result was 0.685. Nutrient simulations also showed reasonable results, with ammonia nitrogen calibration and validation efficiency coefficients both above 0.7; nitrate nitrogen calibration and validation efficiency coefficients both above 0.6; organic nitrogen calibration efficiency coefficient at 0.609, and validation at 0.459; total nitrogen calibration efficiency coefficient at 0.693, and validation at 0.569. The orthophosphate calibration efficiency coefficient was 0.758, with validation at 0.575, and total phosphorus calibration and validation efficiency coefficients both above 0.6. The comprehensive simulation results indicate that the SWAT+ model performs well in long-term hydrological and nutrient simulations for the Feitsui Reservoir watershed. For carbon storage and carbon pool estimation, the SWAT+ model calculates biomass for forests, crops, and other terrestrial vegetation, as well as soil organic carbon. The biomass is then converted to carbon sequestration by multiplying by the carbon content percentage. The SWAT+ model estimated an annual average carbon storage of approximately 411.73 tons per hectare and an annual average biomass of approximately 282.48 tons per hectare in the Feitsui Reservoir watershed, consistent with the forest biomass range specified in the IPCC 2006 guidelines, indicating that the SWAT+ model reasonably simulates terrestrial plant biomass in the Feitsui Reservoir watershed.

In the InVEST model simulation, this study referred to the InVEST model manual and consulted the 2006 national greenhouse gas inventory report by the Intergovernmental Panel on Climate Change (IPCC) for unit carbon sequestration values, including aboveground, belowground, soil, and dead organic matter carbon sequestration. The average annual carbon storage was calculated through map overlay analysis, yielding an estimated annual average carbon storage of approximately 333.7 tons per hectare in the Feitsui Reservoir watershed.

In summary, comparing the results of the SWAT+ and InVEST models, the input reference values for the InVEST model are based on large-scale, regional ranges, such as tropical and subtropical forests, but for specific small-scale areas like a watershed, there is greater uncertainty in obtaining input values that match regional characteristics, though it offers the advantage of rapid and efficient assessment. The SWAT+ model simulation can achieve higher credibility through the parameter calibration and validation process using observed data. However, the disadvantage is the complexity and time-consuming nature of the various processes in the watershed, requiring the handling of large datasets for calculations.

Keywords: SWAT+，InVEST，Ecosystem Services，Carbon Storage