Simen Owen Academic Proceedings Series

3rd International Conference on Education, Environment, Arts and Social Science (EEAS 2026)

Article

Three Methods for Assessing Carbon Storage and Carbon Sink Potential of Temperate Arid Eucalyptus Forest Ecosystems

Zhelong Zhu[1,*]

[1] School of Science, University of Melbourne, Melbourne, Australia
* Correspondence: Zhelong Zhu, School of Science, University of Melbourne, Melbourne, Australia

Abstract: This study adopted an integrated methodological framework combining field plot measurement, long-term carbon flux monitoring, and ecological model simulation to comprehensively evaluate the carbon storage characteristics and carbon sink potential of temperate arid eucalyptus forests in Victoria, Australia. Field surveys were systematically conducted to compare carbon storage across multiple carbon pools in two representative sample plots and to analyze the influence of stand structure on carbon distribution patterns. Long-term net ecosystem exchange data spanning from 1996 to 2014 were applied to explore interannual, seasonal, and diurnal variations in forest carbon flux, as well as the driving effects of key meteorological factors including precipitation, light availability, and temperature. The FullCAM model was further employed to simulate carbon storage dynamics over an 80-year projection period under two native tree restoration scenarios. The results demonstrated that differences in tree diameter class composition and stand age led to distinct total carbon storage between the sample plots. Severe drought conditions significantly weakened forest carbon sink capacity, while light and temperature were identified as the dominant drivers of seasonal and daily carbon exchange dynamics. Continuous planting of native tree species achieved more stable and higher long-term carbon storage compared with conventional rotation management practices. This research provides valuable references for forest carbon inventory, carbon cycle analysis, and the optimization of ecological restoration strategies for similar temperate forest ecosystems globally.

Keywords: carbon storage; carbon flux; eucalyptus forest; ecological modeling; vegetation restoration

Received: 02 June 2026
Revised: 17 July 2026
Accepted: 29 July 2026
Published: 05 August 2026

1. Introduction

Forest ecosystems serve as vital terrestrial carbon reservoirs and play essential roles in regulating atmospheric carbon dioxide concentrations and mitigating global climate change. Many mature forest areas exhibit robust carbon sequestration capacity under natural growth conditions. A range of technical approaches has been developed to assess forest carbon characteristics, and integrating field measurement, long-term flux observation, and ecological model simulation enables multi-scale and comprehensive evaluation of forest carbon status [1]. Wombat Forest in central Victoria is a representative temperate arid eucalyptus forest characterized by complex age structure and pronounced spatial heterogeneity, making it an ideal site for investigating carbon distribution in natural mixed forests.

Most existing studies in this region rely on single-method carbon assessment frameworks. Integrated analyses that jointly leverage field surveys, carbon flux monitoring, and model simulation remain limited [1]. Clarifying how stand structural attributes influence carbon storage—and how meteorological drivers regulate carbon flux across annual, seasonal, and diurnal time scales—is therefore critical. Additionally, evaluating long-term carbon sequestration performance under contrasting native vegetation management regimes can inform the design and implementation of national carbon crediting mechanisms.

This study conducts a systematic assessment of forest carbon storage and sink potential through three complementary research pathways. Field-measured data are used to compare carbon pools between two representative sample plots. Long-term net ecosystem exchange records are analyzed to characterize source–sink dynamics at annual, seasonal, and diurnal resolutions. The FullCAM model is applied to simulate carbon storage trajectories under two native tree restoration scenarios. All input data derive exclusively from field monitoring campaigns, publicly accessible long-term flux databases, and standardized model execution outputs; no questionnaire-based or human-subject experimental data are included [2]. The findings contribute foundational carbon accounting data for Australian temperate forests and offer theoretical grounding for evidence-based forest management and ecological restoration. Globally, research on forest carbon cycling and climate adaptation continues to broaden methodological scope and analytical sophistication.

2. Literature Review

Field investigation based on diameter at 1.3 meters above ground level is the fundamental method for estimating forest carbon storage. Researchers commonly apply allometric equations to convert tree morphological indicators into biomass data for forest carbon calculation. Standard parameter systems have been established to unify carbon conversion protocols in forest-related research [3]. Stand age, tree diameter distribution, and forest history are key factors influencing the spatial distribution of forest carbon pools.

Net ecosystem exchange serves as the primary indicator for assessing whether forest ecosystems function as carbon sources or sinks [3]. Long-term monitoring data indicate that forest carbon sink capacity exhibits notable interannual variability under evolving climatic conditions. Climatic variations and severe weather events significantly influence forest carbon exchange processes. The balance between plant photosynthesis and ecosystem respiration governs the overall carbon budget of forest communities. At seasonal and diurnal scales, light availability and temperature are the dominant drivers of carbon flux variation in temperate forests.

Ecological models constitute essential tools for projecting long-term forest carbon dynamics. A widely validated model has been extensively applied in carbon accounting for woodland ecosystems in Australia. Different afforestation strategies and rotation schedules involving native tree species yield markedly distinct long-term carbon accumulation outcomes in forest restoration initiatives [4]. Ecological modeling supports evidence-based formulation of forest management plans aimed at enhancing carbon sequestration.

Advancements in remote sensing technologies have enabled its widespread use for large-scale forest carbon monitoring and assessment of structural changes. Terrestrial laser scanning provides enhanced technical capability for quantitative evaluation of forest restoration outcomes in Australia [3]. Extensive research efforts have also advanced understanding of coastal and marine carbon ecosystems and carbon dioxide removal approaches, broadening the global carbon cycle research framework. Forest models of diverse types continue to undergo refinement to improve performance under changing climatic conditions.

3. Theoretical Framework and Methodology

3.1. Theoretical Framework

The theoretical foundation of this study integrates forest carbon accounting, ecosystem carbon flux analysis, and ecological model simulation. Forest carbon accounting centers on tree allometric models and standardized carbon conversion protocols, partitioning forest carbon pools into distinct components to quantify carbon storage per unit area. Ecosystem carbon flux analysis classifies carbon sources and sinks based on the sign of net ecosystem exchange and examines relationships between carbon fluxes and meteorological variables across multiple temporal scales. Ecological model simulation establishes alternative vegetation restoration scenarios and projects long-term dynamic trajectories of individual carbon pools using mechanistic models [5]. These three theoretical approaches are mutually reinforcing and collectively enable a multi-dimensional assessment of ecosystem carbon status.

3.2. Methodology

This study employs three independent research methods aligned with its three analytical components [6]. All data originate from publicly accessible field measurements, long-term carbon flux databases, and standardized model simulations. No data from manual questionnaires or human-interaction experiments are included.

3.2.1. Field Measurement for Forest Carbon Storage Assessment

The field research site is Wombat Forest in central Victoria. Two circular sample plots are established. Each plot has a radius of 11 meters and an area of approximately 380 square meters. Tree diameter at 1.3 meters above ground level is measured for all individuals within the plots. Tree biomass is estimated using allometric models based on this diameter measurement [7]. A carbon conversion coefficient of 0.5 is applied to convert biomass into carbon storage values. Forest carbon pools are categorized into large trees, medium trees, small trees, and coarse woody debris. Carbon storage for each component in Plot 4 and Plot 6 is calculated and compared. Sources of measurement uncertainty associated with field operations are also analyzed.

3.2.2. Long-Term Flux Monitoring for Carbon Source and Sink Analysis

Long-term net ecosystem exchange data spanning 1996 to 2014 are analyzed to characterize interannual variability in forest carbon source and sink behavior. Years exhibiting marked differences in precipitation are selected to assess drought effects on carbon sequestration capacity [2]. Monthly mean values are used to identify seasonal patterns in net ecosystem exchange and to evaluate the regulatory roles of light and temperature on seasonal carbon fluxes. Diurnal variations in net ecosystem exchange and solar radiation are examined using two representative days—one clear and one overcast—to elucidate how vegetation carbon uptake responds to varying light conditions.

3.2.3. Ecological Model Simulation for Carbon Sink Potential Evaluation

A widely adopted ecological simulation model is applied in this study [8]. The simulation site is Dookie College in Victoria, Australia, located at latitude −37.03° and longitude 141.30°. The simulation follows the Native Tree Regeneration Method under the Australian Carbon Credit System. The total simulation period spans 80 years, from 2025 to 2105. Scenario One involves a single planting of native tree species adapted to regions with annual precipitation ≥500 mm, without rotational management. Scenario Two implements double-round management: land preparation and replanting occur in year 25 and year 50, respectively, alternating between species suited to high-precipitation (≥500 mm) and low-precipitation (<500 mm) environments. Carbon stocks in tree biomass, litter, and soil—as well as total system carbon—are dynamically tracked under both scenarios. The long-term carbon sequestration performance of the two management approaches is comparatively assessed.

3.3. Research Process

The research is conducted in four sequential phases [9]. The first phase involves data collection and organization, encompassing field survey data from sample plots, long-term carbon flux monitoring records, and essential parameters required for model implementation. The second phase entails computational processing and model execution to derive carbon storage estimates, carbon flux metrics, and scenario-based simulation outcomes. The third phase applies classified statistical analysis to all generated results, enabling characterization of carbon storage and carbon flux patterns within the study forest. The final phase integrates findings into a comprehensive discussion, yielding evidence-informed recommendations for forest carbon management and ecological restoration.

4. Findings and Discussion

4.1. Carbon Storage Characteristics of Different Sample Plots

This part utilizes field measurement data from two sample plots in the Wombat Forest in central Victoria to assess carbon storage across different forest components. The Wombat Forest is a typical temperate eucalyptus forest with mixed species composition, complex age structure, and pronounced spatial heterogeneity. Each sample plot is a circular area with a radius of 11 meters—approximately 380 square meters—and data were processed according to the standardized Excel template provided for instructional purposes [10].

Carbon storage refers to the total amount of carbon fixed per unit area of forest [11]. Biomass was estimated using trunk diameter measured at 1.3 meters above ground level, and a uniform carbon conversion coefficient of 0.5 was applied.

The results indicate that the total carbon storage in Plot 4 is 297.1 Mg C/ha, significantly higher than the 244.0 Mg C/ha observed in Plot 6—a difference of 53.1 Mg C/ha—primarily attributable to variations in carbon storage within larger-diameter trees. Ecological factors contributing to this disparity include a greater proportion of medium- and large-diameter individuals in Plot 4 and a more advanced developmental stage of the forest stand. In contrast, Plot 6 appears to be in an earlier phase of structural development, characterized by a higher abundance of intermediate-diameter trees. Such patterns in carbon distribution commonly occur across forests of differing developmental stages and are influenced by local regeneration history, interspecific and intraspecific competition, and historical environmental conditions (As shown in Table 1) (As shown in Figure 1, 2).

Table 1. Composition of Different Carbon Sinks in the Two Sample Plots (Unit: Mg C/ha)

Carbon pool	Plot 4	Plot 6
Large Trees	268.6	208.9
Medium Trees	2.8	9.7
Small Trees	0.26	0.11
Coarse Woody Debris	25.46	25.35

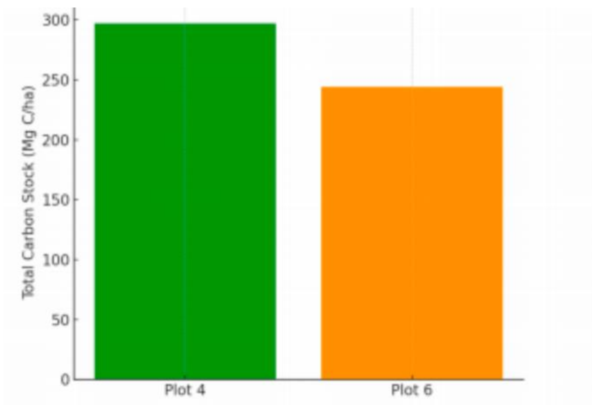

Figure 1. Total Carbon Stock in Two Forest Monitoring Plots

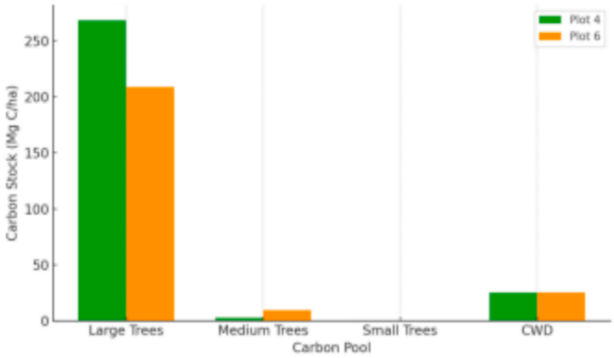

Figure 2. Carbon Pool Breakdown for Plot 4 and Plot 6

Additionally, measurement uncertainties are inherent in field operations, including variability in estimating trunk diameter at 1.3 meters above ground level, imprecision in plot boundary delineation, and subjective assessment of decay status for downed wood. These sources of uncertainty further amplify apparent differences between plots. Consequently, relying on a single small-scale plot is insufficient to characterize landscape-level carbon storage. It is recommended to employ multiple plots, apply standardized survey protocols, and explicitly quantify estimation uncertainty to enhance the reliability and representativeness of regional carbon assessments.

4.2. Multi-Scale Variation Characteristics of Carbon Flux

4.2.1. Interannual Variation of Carbon Source and Sink

From 1996 to 2014, this forest ecosystem functioned predominantly as a carbon sink, with net ecosystem exchange values remaining negative over multiple consecutive years, indicating a net uptake of atmospheric carbon dioxide. Nevertheless, notable interannual variability was observed, including pronounced reductions in carbon sequestration intensity during certain years.

For instance, in 2003, carbon sequestration capacity declined substantially, with the net ecosystem exchange value recorded at −438.8 t C/ha—approximately half the value observed in 1996 (−800.5 t C/ha). Meteorological data for 2003 show radiation intensity and temperature were not unusually low (135.4 W/m² and 8.98 °C, respectively); however, annual precipitation was only 501 mm, the lowest across the entire monitoring period. This indicates that while solar radiation and temperature generally support plant growth, water availability becomes the dominant limiting factor for photosynthesis under severe drought conditions. Concurrently, ecosystem respiration persisted—and may have increased due to thermal stress—contributing to the overall reduction in carbon sink strength.

In years characterized by more favorable moisture conditions or milder climatic conditions, the net ecosystem exchange of the forest system tended to be more negative, reflecting stronger carbon uptake. This temperate forest ecosystem exhibits high sensitivity to variations in water availability. Even when temperature and radiation are sufficient, vegetation fails to achieve effective net carbon assimilation under water-limited conditions.

Collectively, these findings indicate that although the forest maintains a stable carbon sink function over the long term, interannual climate variability—particularly years with markedly reduced precipitation—exerts a substantial influence on carbon uptake performance. In developing forest carbon sink predictions and models, it is essential to move beyond average climatic parameters and explicitly incorporate the effects of anomalous weather conditions on the balance between photosynthesis and respiration [6] (As shown in Table 2) (As shown in Figure 3).

Table 2. Meteorological Factors and Net Ecosystem Exchange of Typical Monitoring Years

Year	NEE (t C/ha)	Radiation (W/m²)	Temperature (°C)	Precipitation (mm)
1996	-800.5	-	-	-
2003	-438.8	135.4	8.98	501

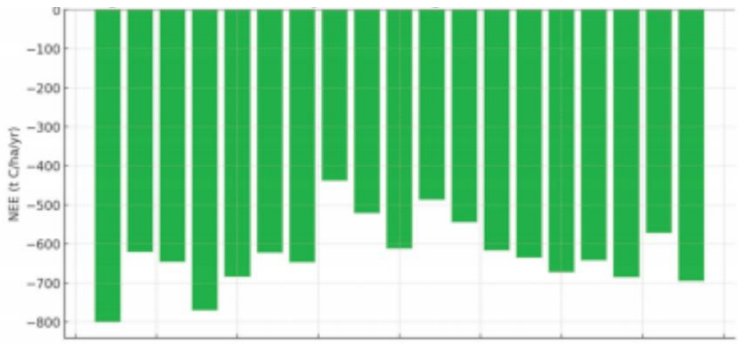

Figure 3. Annual Net Ecosystem Exchange (1996-2014)

As illustrated in Figure 3 and Figure 4, interannual fluctuations in carbon sink capacity correlate closely with variations in annual precipitation.

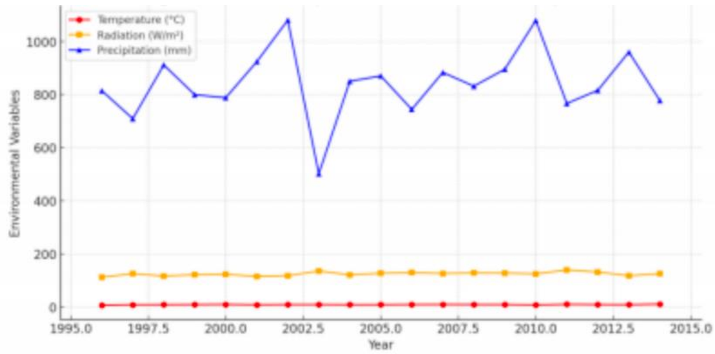

Figure 4. Annual Temperature, Radiation and Precipitation

4.2.2. Seasonal Variation of Carbon Flux

Long-term monthly data reveal pronounced seasonal variation in carbon flux within this forest ecosystem. Net ecosystem exchange is consistently negative from April to August, indicating peak carbon absorption [12]. From November to February of the following year, net ecosystem exchange approaches zero or becomes positive, reflecting a transition from carbon sink to carbon source.

This seasonal pattern is closely linked to variations in light and temperature. During spring and summer, extended daylight duration and strong solar radiation—averaging above 170 W/m²—combined with temperatures near 15 °C create optimal conditions for photosynthesis. Consequently, gross primary productivity exceeds ecosystem respiration, yielding net carbon uptake. In contrast, reduced light availability and declining temperatures during autumn and winter suppress plant growth and shift the balance toward respiration, resulting in net ecosystem exchange approaching zero or turning positive.

Annual precipitation exhibits interannual variability but lacks consistent seasonal periodicity, suggesting that short-term carbon exchange dynamics are primarily governed by light and thermal conditions rather than moisture. Thus, light and temperature jointly regulate the seasonal carbon sink behavior of this ecosystem [13] (As shown in Figure 5).

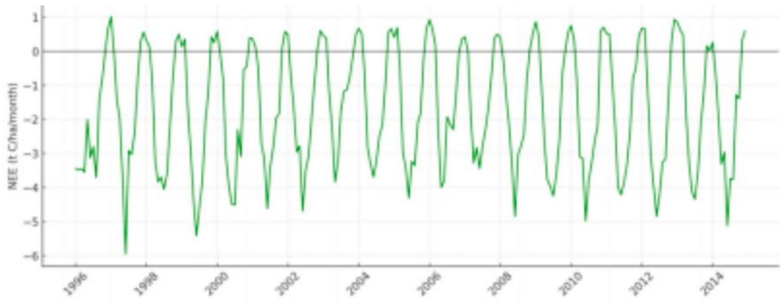

Figure 5. Monthly NEE at DE-Tha (1996-2014)

Figure 5 and Figure 6 collectively illustrate the strong seasonal correspondence between carbon flux and key environmental drivers.

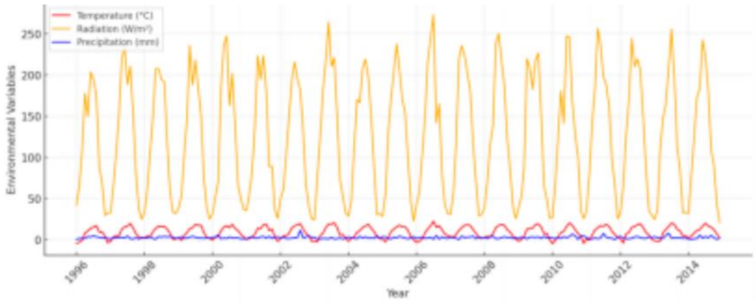

Figure 6. Monthly Temperature, Radiation and Precipitation (1996-2014)

4.2.3. Diurnal Variation of Carbon Flux

Diurnal carbon flux data reveal the daily physiological activity patterns of vegetation. Two representative days were selected for comparative analysis: a clear spring day on May 12, 2011, and a cloudy day on November 30, 2010.

On the clear day, solar radiation followed a pronounced bell-shaped diurnal pattern, peaking near midday at approximately 800 W/m². Concurrently, net ecosystem exchange (NEE) exhibited strong diurnal variation, reaching its maximum carbon uptake rate of approximately −12 μmol $CO_2 \cdot m^{-2} \cdot s^{-1}$ at noon, indicating peak photosynthetic activity under high irradiance.

By contrast, on the cloudy day, solar radiation remained consistently low—generally below 200 W/m²—and showed minimal diurnal variation. NEE remained near zero or slightly positive across most hours, reflecting negligible net carbon assimilation due to insufficient light availability for effective photosynthesis.

This strong dependence of carbon exchange on incident radiation confirms that short-term carbon sink dynamics in temperate forest ecosystems are primarily light-driven rather than governed by temperature or moisture conditions. Even in regions with ample annual precipitation, prolonged cloud cover and reduced irradiance rapidly suppress forest carbon sequestration capacity (As shown in Table 3) (As shown in Figure 7, 8).

Table 3. Key Characteristics of Radiation and Net Ecosystem Exchange on Typical Days

Weather type	Maximum radiation (W/m²)	Peak NEE (μmol/m²/s)	Main characteristics
Sunny day	Nearly 800	-12	Strong net carbon absorption at noon
Cloudy day	No more than 200	Slightly positive	Effective carbon absorption almost stops

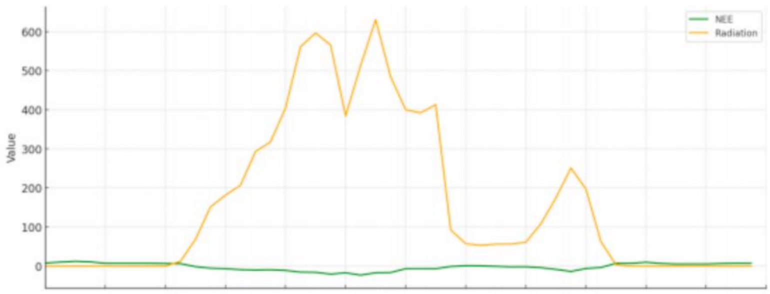

Figure 7. Sunny Day (2011-05-12): NEE and Radiation

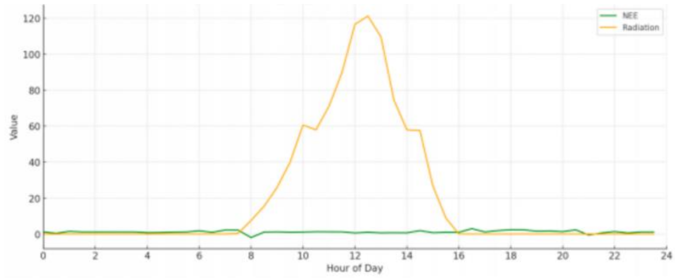

Figure 8. Cloudy Day (2010-11-30): NEE and Radiation

4.3. Simulation Results of Carbon Sink Potential under Different Restoration Scenarios

This study employed the FullCAM model, originally developed by the Australian government, and selected Dookie College in Victoria as the research site to simulate carbon sink potential under various native tree species restoration strategies. Simulations followed the methodological framework of the Native Tree Regeneration Method within the Australian Carbon Credit System to project changes in carbon storage across an 80-year horizon from 2025 to 2105.

Under Scenario One—continuous planting—the carbon storage in aboveground tree biomass increased steadily over time and approached asymptotic stability at approximately 40.5 tC/ha by the 40th year. Soil carbon content rose gradually from an initial level of about 50 tC/ha and ultimately reached 62 tC/ha. While carbon accumulation in litterfall and coarse woody debris proceeded at a slower pace, it exhibited consistent upward trends [14, 15]. The integrated system-level carbon storage converged at 121 tC/ha, reflecting strong long-term structural and functional stability.

In contrast, under rotation management, tree carbon storage declined sharply following each harvest cycle, approaching near-zero values temporarily and driving total plot carbon storage down to a minimum of approximately 56 tC/ha. Although post-harvest residues—including branches, leaves, and wood fragments—transferred into soil organic matter and dead organic matter pools, thereby providing partial buffering, the net carbon accumulation rate remained substantially lower than that achieved under continuous planting [16, 17].

Collectively, for objectives centered on sustained carbon sink enhancement and minimization of anthropogenic carbon loss, continuous planting of native tree species in high-precipitation regions (≥500 mm annual rainfall) represents a more robust and ecologically sustainable strategy. This approach supports steady realization of sequestration potential and delivers consistent, long-term contributions to ecological restoration goals (As shown in Table 4) (As shown in Figure 9, 10).

Table 4. Final Carbon Storage of Each Component under Two Restoration Scenarios (Unit: T C/ha)

Carbon component	Scenario 1 (Continuous planting)	Scenario 2 (Rotation management)
Trees	40.5	Near zero (minimum period)

Debris	Steadily rising	Partial accumulation
Soil	62.0	Increased slightly
Total system	121.0	About 56.0 (minimum period)

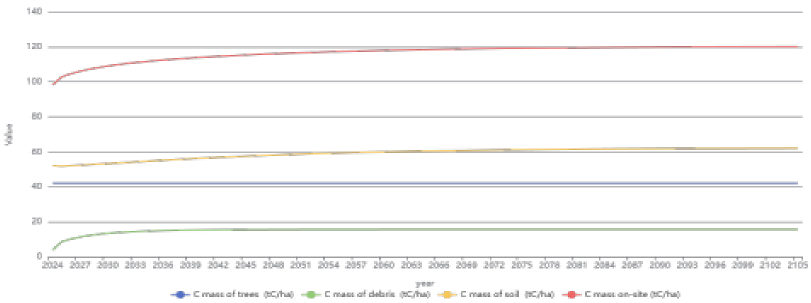

Figure 9. The Changes in Carbon Storage of Each Component under Native Tree Species Continuously Planted in Areas with a Rainfall of ≥ 500Mm

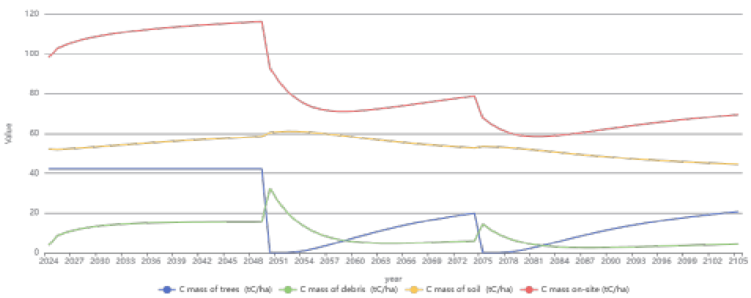

Figure 10. The Changes in Carbon Storage of Each Component of Native Tree Species under Continuous Planting in Areas with Rainfall ≥500Mm

4.4. Comprehensive Discussion

The three assessment methods employed in this study differ in spatial scope and analytical focus. Field measurement provides precise quantification of current forest carbon storage at plot level and elucidates the spatial distribution patterns across carbon pools. Long-term carbon flux monitoring captures temporal dynamics of carbon sources and sinks across annual, seasonal, and diurnal scales, thereby clarifying how forest carbon cycling responds to environmental drivers. Ecological model simulation overcomes temporal constraints inherent in observational data and enables projection of carbon storage trajectories under alternative management scenarios.

Stand structural attributes—particularly tree diameter distribution and stand age—constitute key internal determinants of inter-plot carbon storage variation. Climatic variables including precipitation, solar radiation, and temperature govern carbon flux variability across multiple temporal scales. Human management practices critically shape long-term carbon accumulation pathways in restored forests [11]. Effective forest carbon assessment and planning therefore require integrated consideration of biophysical conditions, climatic context, and ecological restoration objectives to inform site-specific management strategies.

5. Conclusion

This study integrates field plot measurement, long-term carbon flux monitoring, and ecological model simulation to comprehensively assess carbon storage and carbon sink potential in temperate arid eucalyptus forest within Wombat Forest and adjacent areas. The principal findings are summarized below.

First, stand age and tree diameter distribution significantly influence carbon storage across forest plots. Plots characterized by a higher proportion of large-diameter trees and greater stand maturity exhibit elevated total carbon storage. Coarse woody debris carbon storage remains relatively stable in natural forests. Field measurement uncertainties necessitate caution in interpretation; therefore, multi-plot sampling is recommended for robust regional forest carbon inventory.

Second, the studied forest functions as a persistent carbon sink over extended time scales. Prolonged drought conditions substantially diminish carbon sink capacity. Seasonal carbon flux variation is primarily governed by light availability and temperature, with solar radiation serving as the dominant driver of diurnal patterns in vegetation carbon uptake. Climate variability—including infrequent but intense climatic events—must be explicitly incorporated into carbon flux analysis and predictive modeling.

Third, vegetation restoration and management strategies yield markedly different long-term carbon sequestration outcomes. Continuous planting of ecologically appropriate native species in higher-precipitation zones supports sustained growth in ecosystem carbon storage. In contrast, rotation-based management leads to pronounced declines in stored carbon. A continuous planting approach proves more effective for enhancing long-term carbon sink capacity and supporting ecological restoration objectives.

The three assessment methods employed herein—field measurement, long-term flux monitoring, and model simulation—can be synergistically integrated to enable multi-scale, full-cycle evaluation of forest carbon status. These findings offer actionable insights for carbon accounting, carbon cycle research, and vegetation restoration initiatives in analogous temperate forest ecosystems. Future work may refine model parameterization and investigate carbon dynamics under increasingly complex climate and management scenarios.

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