The Carboniferous period as a model for atmospheric carbon sequestration through large-scale vegetation dynamics

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Abstract. The Carboniferous period (ca. 359–299 million years ago) stands as a unique geological epoch characterized by prolific plant growth and significant organic carbon burial, leading to the formation of vast coal deposits. This paper investigates the Carboniferous as a paleoecological model for atmospheric carbon sequestration through large-scale vegetation dynamics. The expansion of swamp forests during this period played a critical role in the drawdown of atmospheric CO_2, contributing to climate cooling and long-term carbon storage. By synthesizing paleobotanical, geochemical, and ecological data, we assess the relevance of this ancient model to contemporary afforestation strategies aimed at mitigating anthropogenic climate change. While the Carboniferous case demonstrates the potential of vegetation as a carbon sink, key limitations, including differences in ecological stability, sedimentation regimes, and fossilization processes, preclude a direct replication of its sequestration efficiency. The study underscores that although afforestation remains a valuable tool within a multifaceted mitigation framework, it cannot, in isolation, achieve the scale of sequestration witnessed in the Carboniferous without complementary technologies and systemic transformations.
Key Words: afforestation, carbon sequestration, Carboniferous period, climate mitigation, CO_2 drawdown, fossil carbon, geobiology, paleoclimate, paleoecology, swamp forests.

Introduction. The Carboniferous period (approximately 359–299 million years ago) represents a unique interval in Earth's history characterized by prolific vegetation growth and significant geobiological transformations. This era witnessed the emergence of extensive swamp forests dominated by lycophytes, ferns, and early gymnosperms, ecosystems that played a critical role in reducing atmospheric carbon dioxide (CO_2) levels and contributed to long-term carbon storage via the formation of coal deposits. The interaction between the biosphere and atmosphere during this period led to profound climatic impacts, including global cooling and glaciation events.

This paper aims to explore the Carboniferous as a paleoecological model for contemporary strategies of carbon sequestration. Specifically, it examines the mechanisms by which terrestrial vegetation influenced atmospheric CO_2 concentrations, the geological and climatic context that facilitated large-scale organic carbon burial, and the relevance — along with the limitations — of applying insights from this period to modern afforestation and reforestation efforts. By integrating paleobotanical data, isotope geochemistry, and ecological theory, we critically assess whether the conditions that enabled massive carbon capture in the Carboniferous can inform viable pathways for mitigating anthropogenic climate change today.

Fossil Forests and Carboniferous Resources. The Carboniferous period, spanning approximately 359 to 299 million years ago, was a significant era in Earth's history, marked by the extensive formation of coal beds. These coal beds originated from vast swampy forests dominated by large ferns, horsetails, and lycophytes (Bonan & Shugart 1989; Jarvis 1989; Riaz et al 2024). The dense vegetation of these forests played a crucial role in the carbon cycle of the time, as they absorbed atmospheric carbon dioxide (CO_2) through photosynthesis and stored it as biomass. Over millions of years, the accumulated plant material was buried and transformed into coal, a major fossil fuel resource today.

Atmospheric CO_2 Concentration During the Carboniferous. During the Carboniferous period, atmospheric CO_2 concentrations were significantly different from today's levels. The extensive growth of forests during this time contributed to a substantial drawdown of CO_2, leading to a cooler global climate and the formation of extensive ice sheets. This period is characterized by a dynamic interplay between the biosphere and the atmosphere, where the proliferation of plant life significantly impacted atmospheric composition (Table 1).

Table 1

Atmospheric CO_2 concentration and forest dynamics in the Carboniferous

Aspect	*Description*	*Reference*
Forest composition	Dominated by large ferns, horsetails, and lycophytes, contributing to extensive coal formation	Bonan & Shugart (1989); Jarvis (1989); Riaz et al (2024)
CO_2 concentration	Significant drawdown of atmospheric CO_2 due to extensive forest growth and coal formation	Fernández-Martínez et al (2017); Jiang et al (2020); Watham et al (2021)
Climate impact	Lower CO_2 levels contributed to cooler global temperatures and glaciation events	Bonan & Shugart (1989); Heath et al (2005); Fernández-Martínez et al (2017)
Carbon sequestration	Forests acted as major carbon sinks, storing carbon in plant biomass and eventually forming coal deposits	Phillips et al (1998); Malhi & Grace (2000); Jiang et al (2020)

Abundance, Density, and Size of Carboniferous Animals Compared to Other Geological Stages. The Carboniferous period, spanning approximately 60 million years, is renowned for its rich biodiversity and the significant size of its fauna, particularly in the coal-forming swamps. This period is marked by a diverse array of plant and animal life, which has been well-documented due to extensive coal mining activities that have unearthed numerous fossils (Taylor & Scott 1983). The abundance and diversity of organisms during the Carboniferous are attributed to the lush vegetation and the unique swampy environments that provided ideal conditions for fossilization (Taylor & Scott 1983).

The Carboniferous period is characterized by a high abundance of both marine and terrestrial organisms. The marine ecosystems were dominated by benthic invertebrates such as calcareous foraminifers and bryozoans, which were widespread in the circumequatorial belt during the Early Carboniferous (Ross & Ross 1985). On land, the coal swamps supported a diverse range of plant and animal life, including large arthropods and early tetrapods, which thrived in the humid, oxygen-rich atmosphere (Taylor & Scott 1983; Kearsey et al 2016).

The size of Carboniferous animals varied significantly, with some species reaching remarkable sizes. For instance, the *Gigantoproductus* brachiopods were notable for their large size and thick shells, thriving in the warm, shallow marine environments of the Late Mississippian (Qiao & Shen 2015). Similarly, the terrestrial ecosystems supported large tetrapods and arthropods, with some of the largest lungfish ever found dating back to this period (Clack et al 2018). The dense vegetation and high oxygen levels likely contributed to the large body sizes observed in many Carboniferous species (Kearsey et al 2016).

Compared to other geological periods, the Carboniferous (Figure 1) is unique in its combination of high biodiversity and large organism sizes. The end-Devonian extinction event had previously reduced faunal diversity, but the Carboniferous saw a resurgence in both marine and terrestrial life forms (Clack et al 2018). In contrast, the subsequent Permian period experienced significant climatic changes and extinctions, leading to a decline in biodiversity and the size of many species (Ross & Ross 1985). The Carboniferous period's warm, humid climate and extensive swamp habitats provided a stark contrast to the cooler, more arid conditions of later periods, which influenced the evolutionary trajectories of many species (Qiao & Shen 2015).

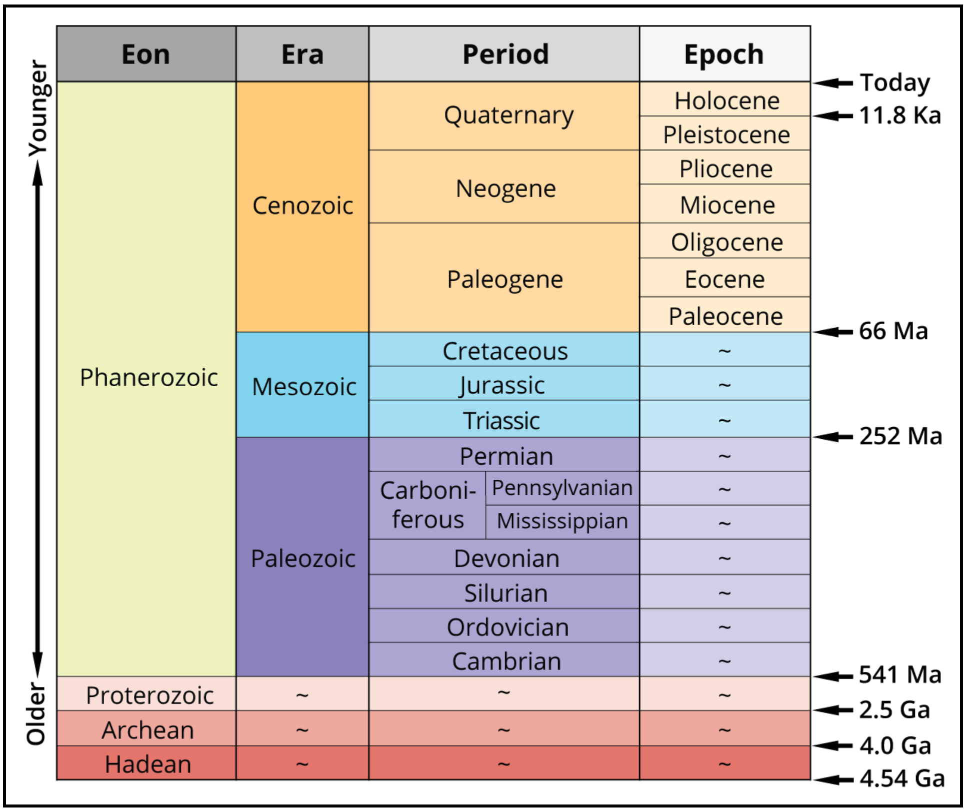

Figure 1. The geological time scale. Image by Jonathan R. Hendricks. This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License. www.digitalatlasofancientlife.org

The Carboniferous Period as a Model for Carbon Sequestration. The Carboniferous period offers a compelling paleoclimatic case study for the potential of large-scale afforestation as a means of atmospheric carbon sequestration. During this period, the proliferation of vast swamp forests — composed predominantly of lycophytes, ferns, and early gymnosperms — coincided with a significant drawdown of atmospheric CO_2 (Phillips et al 1998; Jiang et al 2020). Paleobotanical and geochemical evidence supports the hypothesis that this extensive biomass production contributed to one of the most prominent long-term carbon sinks in Earth’s history (Jiang et al 2020; Malhi & Grace

2000), eventually forming the large coal deposits we exploit today (Fernández-Martínez et al 2017; Jiang et al 2020; Watham et al 2021).

Stable carbon isotope records ($\delta^{13}C$) and paleosol data suggest a marked decrease in atmospheric CO_2 concentrations during the middle to late Carboniferous (Fernández-Martínez et al 2017; Jiang et al 2020; Watham et al 2021), potentially falling from >1000 ppm to levels approaching those of the pre-industrial Holocene (~280 ppm) (Bonan & Shugart 1989; Heath et al 2005; Fernández-Martínez et al 2017). This drawdown has been attributed largely to the burial of organic matter in anoxic wetland environments, where the degradation of plant material was substantially slowed, allowing large quantities of carbon to be sequestered in sediments. Moreover, the high primary productivity of these forests, fueled by a warm, humid climate and abundant shallow water systems, facilitated rapid carbon fixation via photosynthesis.

However, extrapolating the Carboniferous model to modern afforestation efforts requires caution. While it is true that forests can serve as carbon sinks through biomass accumulation (Petrescu-Mag & Gavriloaie 2022) and soil carbon storage (Oroian et al 2023, 2024ab), several limiting factors must be considered. Modern atmospheric CO_2 concentrations exceed 420 ppm (Petrescu-Mag et al 2023), and anthropogenic emissions continue to rise. Additionally, unlike in the Carboniferous, modern ecosystems are fragmented, often degraded, and exist in a context of rapid climate change, which may limit their sequestration capacity.

Furthermore, the long-term sequestration that occurred during the Carboniferous was predicated on the burial and fossilization of plant material—processes not easily replicated in today's managed forests, where disturbance and decay release much of the stored carbon back into the atmosphere. There is also the issue of land availability, biodiversity trade-offs, and potential albedo effects of large-scale forestation in high-latitude regions.

In conclusion, while the Carboniferous period provides a paleoecological precedent suggesting that abundant vegetation can significantly reduce atmospheric CO_2, the mechanisms involved were unique to that era and not directly transferable to contemporary conditions. Nevertheless, afforestation, when combined with other strategies such as soil carbon enhancement, carbon capture and storage (CCS), and reduced deforestation, remains a scientifically valid — albeit partial — component of a broader climate mitigation framework.

Conclusions. The Carboniferous period provides a valuable paleoclimatic analogue for understanding the potential of large-scale vegetation in regulating atmospheric carbon dioxide through long-term sequestration mechanisms. The proliferation of vast swamp forests during this era contributed to a significant and sustained drawdown of atmospheric CO_2, ultimately facilitating the deposition of extensive coal beds that act as geological carbon reservoirs to this day. These ancient ecosystems functioned as highly efficient carbon sinks, largely due to unique combinations of climate, hydrology, and sedimentation dynamics — factors that are not fully replicable in the modern context.

While the underlying biological process of carbon fixation via photosynthesis remains fundamentally unchanged, the environmental, ecological, and anthropogenic variables influencing today's biosphere introduce significant constraints. Modern afforestation initiatives face challenges such as limited land availability, biodiversity trade-offs, climatic instability, and disturbance-driven carbon release, all of which complicate direct analogies with Carboniferous processes. Moreover, the deep-time sequestration observed in the Carboniferous was made possible by the long-term burial of biomass in anoxic environments — a scenario rarely achievable under current land-use and conservation practices.

Therefore, while the Carboniferous model supports the principle that vegetation can act as a major driver of atmospheric CO_2 reduction, its application must be viewed through a critical lens. Afforestation and reforestation, when strategically implemented and integrated with other mitigation measures such as carbon capture and storage (CCS), soil carbon management, and reduced deforestation, may contribute meaningfully to climate stabilization. However, these efforts alone are insufficient to match the scale and permanence of sequestration achieved during the Carboniferous. A scientifically grounded and multifaceted approach is essential for any effective long-term carbon management strategy.

Conflict of Interest. The authors declare that there is no conflict of interest.

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