Earth system model-based assessment of carbon removal potential and climate effects of afforestation

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Abstract: In the context of global climate change, the ecological and climatic effects of afforestation as a key carbon removal technology are regulated by soil moisture. In this study, based on UVic_ESCM, we modelled the long-term effects of afforestation on carbon cycling and climate in the mid-latitude region of the Northern Hemisphere under the SSP5-8.5 scenario with different soil moisture (A1:330 kg/m², A2:360 kg/m², A3:390 kg/m²). The results showed that A3 significantly enhanced CO_2 uptake capacity, reducing atmospheric carbon by 203.8 Gt C and increasing terrestrial carbon by 267.9 Gt C in 2099, which was four times more efficient than that of A1, but the long-term carbon sink rate slowed down due to saturation effect.A3 achieved a cumulative reduction of 0.32°C in surface temperature by enhancing transpiration and optimizing the energy balance, while A1 counteracted to cause a slight warming (+0.21°C). Regional analysis showed significant carbon gain in tropical plants and dominance of carbon accumulation in temperate soils. This study reveals that soil moisture is a key variable in optimizing the climate benefits of afforestation projects, providing a quantitative basis for regional strategy development and emphasizing the need to balance carbon sink gains with water sustainability.

1 Introduction

Global climate change is becoming increasingly severe, with greenhouse gas emissions driving pronounced global warming. The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) highlights that the global mean surface temperature in 2023 was approximately 1.1°C above pre-industrial levels, and the rate of warming continues to accelerate [1]. While the Paris Agreement aims to limit global temperature rise to well below 2°C and pursue efforts to restrict it to 1.5°C, current trajectories suggest a mere 5% probability of staying below the 2°C threshold [2]. In this context, Carbon Dioxide Removal (CDR) technologies are increasingly critical for mitigating climate risks.

Afforestation as a CDR approach, enhances photosynthetic carbon sequestration by expanding forested areas, thereby actively removing atmospheric CO2. Forest ecosystems play a pivotal role in the global carbon cycle due to their robust carbon sequestration capacity, significantly contributing to climate change mitigation by slowing global warming [3]. Studies employing Shared Socioeconomic Pathways (SSPs) and climate mitigation scenarios project that global forests will continue to act as carbon sinks over extended periods. Estimates suggest that forests could sequester 1.2–5.8 Gt CO_2 annually worldwide in the coming century. However, under baseline scenarios excluding climate mitigation policies, forest carbon fluxes exhibit substantial variability, ranging from −0.8 to 4.9 Gt CO_2 yr^{-1} [4]. This disparity underscores the critical influence of climate policies on forest carbon sink functionality and emphasizes the necessity of integrating policy factors into assessments of forest carbon potential.

Afforestation mitigates climate change by expanding forested areas to enhance photosynthetic CO_2 sequestration. Irrigation, a key factor influencing forest ecosystems, significantly modulates soil moisture and surface energy partitioning. Under low soil moisture conditions, reduced evapotranspiration increases sensible heat flux, elevating near-surface temperatures. Conversely, irrigation-driven soil moisture enhancement raises evapotranspiration, lowering the sensible-to-latent heat ratio and inducing surface cooling [5]. Previous studies demonstrate irrigation's efficacy in regulating near-surface temperatures and alleviating regional warming. Gallagher et al. showed that irrigation-induced evaporative cooling effects dominate and suppress the warming trend, and that this localized cooling is more significant than the regional greenhouse effect due to increased atmospheric water vapor [6]. In the study by Wu et al. on irrigated farmland in Central Asia, the increase in latent heat flux and decrease in sensible heat flux due to irrigation was further exacerbated when the temperature increased by 2°C, resulting in a more pronounced decrease in surface air temperature. These findings highlight irrigation-augmented afforestation as a viable strategy for localized climate regulation [7].

Nevertheless, afforestation's climatic impacts are multifaceted, mediated through biophysical feedback mechanisms such as altered surface albedo and

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roughness. These feedbacks may counteract the benefits of carbon sequestration. For instance, increased forest cover enhances carbon sinks but may also reduce surface albedo, amplifying solar radiation absorption and partially offsetting cooling effects [8].

Current global assessments of afforestation's carbon removal potential and climate responses remain incomplete. Most studies focus on isolated factors or specific regions, lacking systematic analyses across long-term temporal and large spatial scales. Regional variations in climate, soil, and vegetation conditions lead to divergent carbon sequestration efficiencies and ecological impacts. Advanced modelling approaches and methodologies are therefore required to investigate these dynamics from a broader perspective.

This study utilizes the University of Victoria Earth System Climate Model to conduct long-term simulations that comprehensively evaluate afforestation's carbon removal potential, accounting for irrigation effects and biophysical feedbacks. By addressing these multidimensional interactions, the research aims to provide a robust scientific foundation for designing targeted and effective climate mitigation strategies.

2 Methods

2.1 Model Description

This study employs version 2.9 of the University of Victoria Earth System Climate Model (UVic_ESCM) to simulate the climatic effects of afforestation. The UVic_ESCM, a widely utilized tool for assessing long-term climate change, has been extensively validated across multiple dimensions for pre-industrial to modern climatic conditions [9]. The model dynamically couples a three-dimensional ocean general circulation model, an atmospheric energy-moisture balance model, and a land surface module. The land module, based on the TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics) model developed by the Hadley Centre, simulates vegetation dynamics and carbon cycle processes [10]. The horizontal resolution of the model is 3.6° longitude × 1.8° latitude.

2.2 Experimental Design

Under the SSP5-8.5 scenario, the UVic-ESCM was used to investigate the climatic impacts of afforestation in the Northern Hemisphere mid-latitude region (30°N–60°N) from 2030 to 2099. To establish a control simulation (C) without afforestation until 2029, the model was initialized with pre-industrial boundary conditions and spun up for 10,000 years until 1765. Historical CO_2 emission data were then incorporated to simulate atmospheric CO_2 levels from 1765 to 2000, followed by the application of SSP5-8.5 scenario emissions from 2000 to 2029. Throughout this process, the influence of non-CO_2 greenhouse gases was excluded, and boundary conditions for other model components remained unchanged.

In the experimental simulations, three soil moisture levels—330 kg/m^2 (A1), 360 kg/m^2 (A2), and 390 kg/m^2 (A3)—were prescribed to simulate varying irrigation intensities for afforestation. These configurations aim to investigate the responses and mechanisms of afforestation under different irrigation regimes, including effects on atmospheric CO_2 concentrations, surface temperature, terrestrial carbon stocks, albedo, and evapotranspiration-precipitation feedbacks. This systematic approach enables a robust evaluation of afforestation as a CDR technology, providing critical insights for future climate mitigation strategies.

3 Results and discussion

3.1 Carbon removal effects of afforestation

Afforestation combined with irrigation-enhanced soil moisture effectively reduces atmospheric CO_2 concentrations. Compared to the control run, afforestation under varying soil moisture conditions exhibits significant differences in CO_2 mitigation efficiency. Under low soil moisture (A1), CO_2 concentrations decreased by 0.62 ppm relative to the control in 2030, accumulating to a total reduction of 23.62 ppm by 2099, with an annual reduction rate of 0.33 ppm, indicating a gradual decline. Moderate moisture conditions (A2) substantially enhanced CO_2 sequestration, with concentrations decreasing from an initial reduction of 1.76 ppm to 80.47 ppm by 2099, yielding a cumulative decline of 78.71 ppm and an annual rate of 1.13 ppm—3.4 times more efficient than the low-moisture scenario. High soil moisture (A3) demonstrated the most pronounced carbon sink capacity: CO_2 concentrations declined from 1.97 ppm to 96.01 ppm by 2099, achieving a total reduction of 94.04 ppm at an annual rate of 1.35 ppm, quadrupling the efficiency of the low-moisture scenario. These results highlight that elevated soil moisture significantly enhances vegetation carbon sequestration potential. Long-term dynamics reveal a deceleration in CO_2 reduction rates across all moisture conditions over time. For instance, under high moisture (A3), the annual reduction rate decreased from 1.7 ppm during 2030–2050 to 0.4 ppm in 2090–2099, likely due to saturation thresholds in soil water retention or vegetation growth. Furthermore, while the reduction trajectories of A2 and A3 followed similar trends, A3 consistently maintained higher efficiency, suggesting that increasing soil moisture from 360 kg/m^2 to 390 kg/m^2 unlocks additional carbon sequestration potential. These findings underscore that strategically optimizing soil moisture levels in afforestation projects can significantly amplify CO_2 absorption efficiency, providing critical insights for refining regional afforestation strategies (Figure 1).

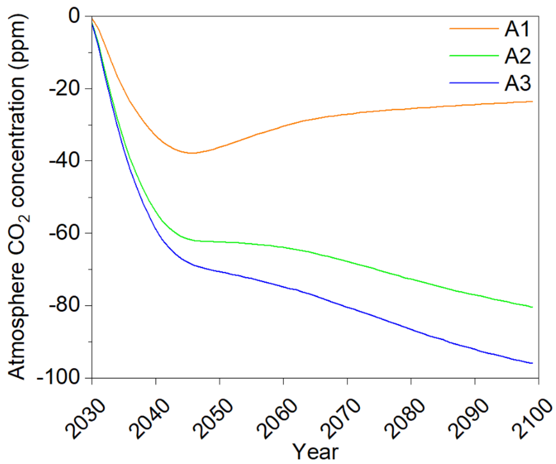

Figure 1. Effects of different soil moisture settings on atmosphere CO_2 concentration

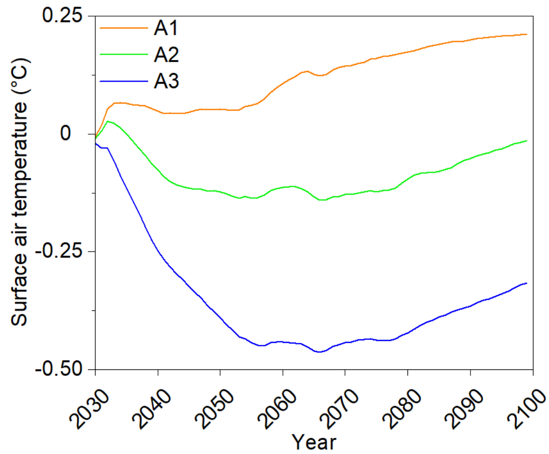

Figure 2. Effects of different soil moisture settings on surface air temperature

According to simulations conducted with the UVic model, afforestation under varying soil moisture conditions exhibits significant differences in its impact on surface air temperature (SAT). Under low soil moisture (A1), SAT increased gradually from −0.006°C in 2030 to 0.21°C by 2099, indicating a slight warming trend with an annual rate of approximately 0.003°C. This suggests that afforestation's cooling effect is limited under low moisture conditions, likely due to insufficient evapotranspiration or changes in surface albedo from increased vegetation cover, which fail to effectively counteract greenhouse warming. Under moderate soil moisture (A2), SAT trends were more complex: after a brief initial rise (2030–2035), temperatures shifted to a sustained decline, decreasing from −0.001°C to −0.013°C by 2099, with a minimal overall cooling effect (annual rate of −0.00006°C). This pattern indicates that while afforestation's cooling potential is enhanced under moderate moisture, it remains constrained by intermediate soil moisture levels, limiting the full expression of vegetation-driven evaporative cooling. In contrast, high soil moisture (A3) yielded the most pronounced cooling effect. SAT decreased steadily from −0.019°C in 2030 to −0.32°C by 2099, achieving a cumulative cooling of approximately 0.3°C (annual rate of −0.004°C). This result underscores the significant role of high moisture in amplifying afforestation's cooling potential, likely mediated through enhanced evapotranspiration, improved surface energy balance, and suppressed greenhouse gas concentrations due to increased carbon sequestration (Figure 2). In summary, soil moisture is a critical determinant of afforestation's cooling efficacy. Low moisture conditions result in limited or even slight warming effects, whereas high moisture significantly enhances cooling, particularly over long-term scales. These findings provide critical insights for optimizing regional afforestation strategies: prioritizing high-moisture afforestation in humid regions can maximize cooling benefits, contributing to global warming mitigation efforts.

3.2 Impact of afforestation on global carbon pools

By 2099, global carbon pool dynamics under the three afforestation scenarios exhibited pronounced gradient differences, closely linked to soil moisture conditions. In the atmospheric carbon pool, the reduction in atmospheric carbon escalated from −50.1 Gt C (A1) to −203.8 Gt C (A3) as soil moisture increased, indicating a substantial enhancement in photosynthetic activity and carbon uptake efficiency under high moisture regimes. This trend aligns with earlier CO_2 concentration simulations, further validating soil moisture as a critical determinant of carbon sink capacity. Terrestrial carbon pool changes were particularly striking: A1 increased terrestrial carbon by 64.8 Gt C, while A3 achieved a 267.9 Gt C increase—approximately 4.1 times greater than A1. This reflects synergistic effects among vegetation biomass accumulation, litter decomposition, and soil organic carbon sequestration under elevated moisture conditions. Notably, the decline in oceanic carbon storage may arise from two mechanisms: (1) reduced oceanic carbon uptake rates due to lowered atmospheric CO_2 concentrations from afforestation, and (2) diminished reliance on oceanic carbon sinks as terrestrial carbon stocks expands. However, this phenomenon requires further validation through coupled ocean-atmosphere carbon exchange modelling. In terms of carbon allocation, the terrestrial carbon gain in A3 (267.9 Gt C) far exceeded atmospheric carbon reduction (−203.8 Gt C), suggesting that beyond direct carbon sequestration, high soil moisture may contribute to net carbon pool growth via enhanced ecosystem stability or suppressed soil respiration emissions (Table 1).

Table 1. Changes in global carbon pools due to three sets of experiments in 2099

Experimental groups	Atmospheric carbon (Gt C)	Oceanic carbon (Gt C)	Land carbon (Gt C)
A1	-50.1	-14.7	64.8
A2	-170.8	-43.9	214.7
A3	-203.8	-64.1	267.9

At the global scale, the results of all three experimental groups significantly increased the terrestrial carbon pool, especially the most significant in A3, which was closely related to the increase in soil moisture and the increase in irrigation intensity. Changes in plant carbon and soil carbon varied significantly in different regions, and these differences were related to a variety of factors such as local climate, soil type, vegetation cover, and irrigation conditions, etc. The plant carbon contents of A2 and A3 increased significantly in the areas where afforestation was implemented, and the plant carbon contents of A1 increased in the high latitude areas in the northern hemisphere in addition to these areas, because A1 increased the atmospheric surface temperature, which facilitated the growth of vegetation. The reason is that A1 increases the atmospheric surface temperature and promotes the growth of vegetation. In addition, plant carbon increased in otherwise arid regions such as northern Africa and some parts of Australia because increased irrigation facilitated the hydrological cycle and increased localized precipitation, which provided more favourable conditions for vegetation growth. In the tropics, such as northern South America and central Africa, the increase in plant carbon is not as pronounced, and even decreases in some localized areas. This may be because these regions already have abundant precipitation and high air humidity, and the limiting factors for vegetation growth have shifted more towards soil fertility and light conditions than moisture (Figure 3).

Changes in soil carbon showed significant regional differences. In the mid-latitude regions of the northern hemisphere, the increase in soil carbon showed a synergistic effect with the increase in plant carbon, especially in A3. This suggests that in these regions, enhanced vegetation growth not only directly increases plant carbon stocks, but also promotes the accumulation of soil organic carbon through pathways such as vegetation apomixis and root secretions. Unlike A2 and A3, A1 showed a decrease in soil carbon, and the increase in soil moisture was accompanied by an increase in temperature, which led to higher soil microbial activity and accelerated decomposition of soil organic carbon, resulting in a decrease in soil carbon (Figure 4). In summary, the effects of temperature change on plant carbon and soil carbon are multifaceted and require comprehensive consideration of multiple processes such as vegetation growth, soil carbon decomposition and sequestration. When formulating afforestation strategies, the effects of temperature change on different regions should be fully considered to maximize the effect of carbon sequestration.

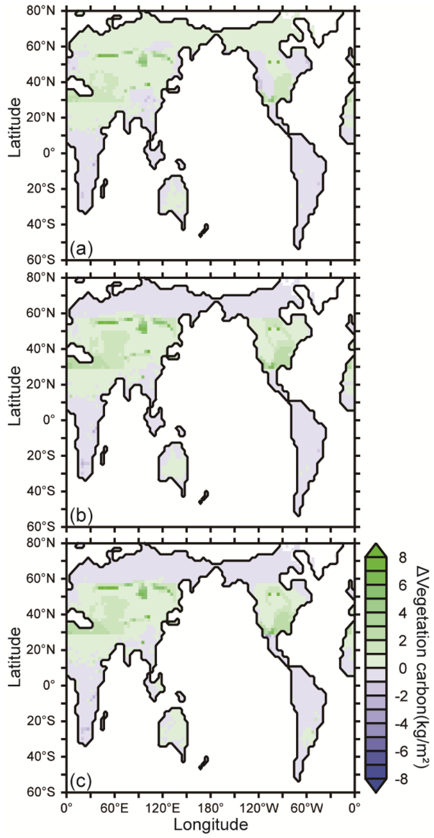

Figure 3. Effects of different soil moisture settings on vegetation carbon

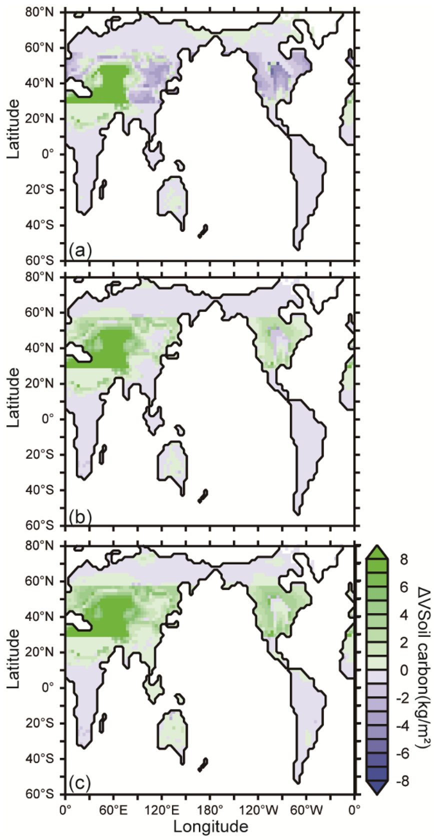

Figure 4. Effects of different soil moisture settings on soil carbon

3.3 Ecological effects of afforestation

Globally, afforestation exerts multifaceted impacts on ecological and climatic systems. Soil respiration rates in experimental groups were consistently higher than those in the control run, with A2 reaching peak values. This suggests that under moderate moisture conditions, microbial activity and root respiration are significantly enhanced, likely due to optimized moisture conditions promoting organic matter decomposition. However, A3 exhibited slightly reduced respiration rates compared to A2, indicating that excessive soil moisture saturation under high humidity may limit oxygen availability, thereby suppressing microbial processes.

Afforestation increases vegetation cover, enhancing light absorption and reducing surface albedo, which alters surface energy balance. Additionally, afforestation modifies hydrological processes by shifting precipitation-evaporation dynamics, as increased vegetation cover elevates evapotranspiration. Notably, the evapotranspiration change in A3 was smaller than in A2, potentially linked to improved soil water retention under high moisture conditions, which reduces evaporative losses. This mechanism indirectly supports A3's pronounced cooling effects (Table 2).

Table 2. Effects of afforestation on key ecological variables under different soil moisture conditions in 2099

Property	C	A1	A2	A3
Soil respiration (Pg C yr-1)	98.2	108.4	111.8	110.2
Surface albedo	0.1632	0.1604	0.1607	0.1615
Precipitation minus Evaporation (kg m^{-2} yr^{-1})	0.03052	-0.1538	-0.1867	-0.1462
soil temperature (°C)	18.02	18.18	17.82	17.29

4 Conclusion

In this study, we used UVic_ESCM to simulate the impacts of afforestation on climate and carbon cycle under different soil moisture conditions, revealing the central role of soil moisture in regulating carbon sink efficiency and cooling effect. It was found that the carbon sink capacity was positively correlated with soil moisture, and high soil moisture (A3) significantly enhanced the carbon sequestration capacity of vegetation, reducing the atmospheric CO_2 concentration by 203.8 Gt C in 2099 compared with that in the control run, and increasing the terrestrial carbon pool by 267.9 Gt C, with an efficiency of more than four times of that of the low-moisture group (A1). However, the long-term carbon sink rate slowed down with the increase of humidity, suggesting that the soil water holding capacity or vegetation growth might be close to saturation. or vegetation growth may be close to the saturation threshold. The cooling effect was dependent on humidity optimization, with high humidity conditions achieving significant cooling (0.32°C reduction in SAT in 2099) through enhanced transpiration and surface energy redistribution, while low humidity (A1) inversely led to slight warming (+0.21°C) due to reduced surface albedo. The ecological response was multidimensional, with the highest soil respiration rate (111.8 Pg C yr^{-1}) at moderate humidity (A2), but high humidity (A3) enhanced soil carbon stocks by inhibiting decomposition. In addition, A3 had the least negative precipitation-evaporation (-0.1462 kg m^{-2} yr^{-1}), reflecting the synergistic effect of its water retention capacity and cooling. The regional fitness differences showed that the plant carbon increment in the tropics was significantly driven by high humidity, while the advantages of soil carbon accumulation were prominent in temperate and high latitude regions, which need to be combined with local climate and soil conditions to optimize silvicultural strategies. In practice, the implementation of high humidity afforestation in humid regions is preferred to maximize carbon sinks and cooling benefits, but the use of water resources and ecological risks need to be balanced. Future research needs to deepen long-term dynamic modelling and integrate ocean-land carbon exchange mechanisms to improve global assessment.

Acknowledgments

This research is supported by the Fundamental Research Funds for the Central Universities (202242001).

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