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Carbon Sequestration Potential of C3 vs. C4 Plants Under Climate Change Conditions

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Abstract- The accelerating rise in atmospheric carbon dioxide (CO_2) concentrations has intensified efforts to enhance terrestrial carbon sinks, particularly through strategic deployment of C_3 and C_4 photosynthetic pathways. This study synthesizes current knowledge on the carbon sequestration potential of C_3 plants, which benefit markedly from CO_2 enrichment but suffer from photorespiration and nutrient constraints, and C_4 plants, which maintain efficiency under heat, drought, and low CO_2 conditions due to their biochemical CO_2-concentrating mechanism. We review field-based flux measurements, remote sensing classification, and genome-scale metabolic models to quantify net primary production responses, soil carbon inputs, and distributional shifts under projected climate scenarios. Findings indicate that C_3 afforestation can maximize sequestration in temperate regions when nutrient limitations are managed, while C_4 bioenergy crops offer robust carbon capture and water-use advantages in warmer, water-limited biomes. We recommend region-specific species selection, integrated methodological frameworks combining eddy-covariance, high-resolution imagery, and mechanistic models, and exploration of synthetic biology and machine-learning tools to refine sequestration estimates. This comprehensive approach informs land-management and policy strategies aimed at mitigating climate change through optimized carbon-negative land uses.

Keywords- C_3 photosynthesis; C_4 photosynthesis; carbon sequestration; elevated CO_2; water-use efficiency; photorespiration; drought resilience; bioenergy crops

I. INTRODUCTION

Global carbon cycle & role of terrestrial vegetation

The global carbon cycle encompasses the exchange of carbon among atmosphere, oceans, land, and geosphere. Since the pre-industrial era, anthropogenic CO_2 emissions from fossil fuel combustion and land-use change have elevated atmospheric CO_2 from roughly 280 ppm to over 410 ppm by 2020, contributing to a ~1 °C rise in global mean temperature (IPCC 2022). Terrestrial vegetation acts as a major carbon sink, sequestering nearly 30 percent of annual anthropogenic emissions through photosynthesis and soil carbon storage. Enhancing these natural sinks is therefore critical to mitigating further atmospheric CO_2 accumulation and achieving climate stabilization goals.

Distinction between C_3 and C_4 photosynthesis

Plants utilize two primary photosynthetic pathways—C_3 and C_4—to fix atmospheric CO_2 into organic compounds. In C_3 photosynthesis, Rubisco catalyzes CO_2 fixation into a three-carbon compound (3-phosphoglycerate), but this pathway incurs substantial photorespiratory losses under high temperature and low ambient CO_2. In contrast, C_4 plants possess a biochemical CO_2-concentrating mechanism: phosphoenolpyruvate carboxylase initially fixes CO_2 into four-carbon acids in mesophyll cells, which are then decarboxylated in bundle-sheath cells to feed the Calvin cycle at elevated CO_2 concentrations, thereby minimizing photorespiration and improving water-use efficiency (Sage).

Significance of comparing C_3 vs. C_4 for climate mitigation

Differential responses of C_3 and C_4 plants to elevated CO_2, rising temperatures, and drought stress have profound implications for carbon sequestration potential. Elevated CO_2 generally stimulates photosynthetic rates and biomass accumulation more in C_3 species, whereas C_4 species maintain higher water-use efficiency and thermal tolerance under heat and moisture stress. Understanding these contrasts is essential for land-management decisions—such as selecting species for afforestation, bioenergy crops, or grassland restoration—to maximize carbon uptake under future climate scenarios (Kumar and Singh; Ciais and Friend).

Research objectives & paper structure

This paper aims to assess and compare the carbon sequestration capacities of C_3 versus C_4 plants under projected climate-change conditions. Section II reviews the literature on sequestration mechanisms; Section III examines physiological and metabolic pathways; Section IV analyzes the impacts of elevated CO_2, temperature, and drought; Section V discusses methodological approaches; Section VI synthesizes findings and policy implications; and Section VII concludes with recommendations for future research.

II. LITERATURE REVIEW

Carbon sequestration in C_3 plants

C_3 plants dominate temperate and boreal biomes, fixing CO_2 via Rubisco in the Calvin–Benson cycle to produce 3-phosphoglycerate. Genome-scale metabolic modeling by Wang et al. shows that C_3 species channel a substantial fraction of assimilated carbon into structural biomass and root exudates, which in turn foster soil organic carbon stabilization through aggregate formation and microbial processing (Wang et al.). Moreover, Li, Zhang, and Shi demonstrate that under drought conditions elevated CO_2 disproportionately benefits C_3 species, enhancing both above- and below-ground biomass and increasing carbon inputs into soil via greater root turnover (Li, Zhang, and Shi).

At elevated atmospheric CO_2, C_3 photosynthesis initially up-regulates: increased CO_2 availability at Rubisco's active site reduces photorespiration, thus boosting net assimilation rates and water-use efficiency (Farquhar, Ehleringer, and Pearcy). However, sustained exposure often triggers photosynthetic acclimation, marked by down-regulation of Rubisco content and shifts in leaf nitrogen allocation, which moderate the long-term stimulation (Farquhar, Ehleringer, and Pearcy). Despite this, Keenan et al. report that in temperate grasslands subjected to both elevated CO_2 and episodic heat or drought, net ecosystem carbon uptake remains positive across seasons, indicating that initial gains in C_3 carbon sequestration can persist at the ecosystem scale (Keenan et al.).

Carbon sequestration in C_4 plants

C_4 plants employ a CO_2-concentrating mechanism in which phosphoenolpyruvate carboxylase in mesophyll cells fixes CO_2 into four-carbon acids, which are then decarboxylated in bundle-sheath cells to elevate CO_2 around Rubisco. This arrangement sharply reduces photorespiration, conferring superior photosynthetic efficiency under high light and temperature (Taylor et al.; Still et al.). Taylor et al. quantify that C_4 grasses can exhibit 20–30 percent higher intrinsic water-use efficiency than C_3 counterparts, translating into greater biomass accumulation per unit water transpired (Taylor et al.). Still et al.'s optimality models predict that under low ambient CO_2 and warming scenarios, C_4 taxa maintain higher carbon assimilation rates, making them key contributors to sequestration in tropical and subtropical ecosystems (Still et al.).

Because the C_4 CO_2 pump nearly saturates Rubisco at current and projected CO_2 levels, direct photosynthetic stimulation under elevated CO_2 is limited: Taylor et al. observed minimal further gains in assimilation when CO_2 rose from 400 to 600 ppm (Taylor et al.). Nonetheless, Havrilla et al. show that in midlatitude dryland steppes, C_4 grasses sustain positive net ecosystem exchange during prolonged dry periods conditions under which C_3 productivity collapses thereby continuing to sequester carbon under extreme heat and moisture stress (Havrilla et al.).

Ecosystem-scale and field-flux studies

Eddy-covariance measurements in mixed C_3/C_4 grasslands reveal complementary daily and seasonal uptake patterns. Ciais and Friend deployed flux towers over a Mediterranean grassland mosaic and found that C_3-dominated patches drove strong midday CO_2 uptake under elevated CO_2, whereas C_4 patches maintained steadier uptake under midday heat stress (Ciais and Friend). Using flux partitioning, they further showed C_3 gross primary productivity peaking in spring and autumn, while C_4 contributions maximized in summer, underscoring the seasonal complementarity of the two pathways.

In arid ecosystems experiencing shrub encroachment into C_4 grasslands, Walter and Smith documented state transitions that enhance soil carbon stocks. Deep-rooted shrubs deposit carbon at greater soil depths and produce more recalcitrant litter than grasses; over decadal timescales, these inputs can exceed losses from increased fire frequency or evaporation, leading to net gains in long-term carbon storage (Walter and Smith).

III. PHYSIOLOGICAL & METABOLIC MECHANISMS

C_3 biochemical pathway

The C_3 photosynthetic pathway centers on the Calvin–Benson cycle, in which ribulose-1,5-bisphosphate (RuBP) is carboxylated by the enzyme Rubisco to form two molecules of 3-phosphoglycerate. These three-carbon intermediates are then phosphorylated and reduced to triose phosphates, which serve as the building blocks for sucrose and starch synthesis. Under current atmospheric CO_2 concentrations, however, Rubisco's dual affinity for O_2 leads to a significant fraction of reactions resulting in photorespiration: the oxygenation of RuBP, generating one molecule of 3-phosphoglycerate and one of 2-phosphoglycolate. The latter must be metabolically recycled via the energetically costly photorespiratory pathway, releasing CO_2 and ammonia, thereby reducing net carbon gain by up to 25 percent on warm, sunny days (Farquhar, Ehleringer, and Pearcy). The high ATP and reducing-equivalent costs of photorespiration also lower water-use efficiency, since stomatal opening must remain higher to supply CO_2, increasing transpirational water loss. Consequently, C_3 species often exhibit lower photosynthetic efficiency under conditions of high light, heat, and low ambient CO_2.

C_4 biochemical pathway

C_4 plants have evolved a biochemical CO_2-concentrating mechanism that spatially separates initial CO_2 fixation from the Calvin cycle. In mesophyll cells, phosphoenolpyruvate carboxylase (PEPC) fixes bicarbonate (HCO_3^-) to phosphoenolpyruvate (PEP), forming four-carbon acids (typically malate or aspartate). These C_4 acids diffuse into tightly packed bundle-sheath cells, where decarboxylation releases CO_2 at concentrations up to tenfold higher than in the ambient air. The concentrated CO_2 is then assimilated by

Rubisco in the Calvin cycle, virtually eliminating photorespiration. This Kranz anatomy characterized by a wreath-like arrangement of bundle-sheath cells around vascular bundles coupled with the biochemical pump, boosts net photosynthetic rates and water-use efficiency, particularly under high light and temperature (Sage). Because PEPC has a much lower affinity for O_2 than Rubisco, the C_4 system maintains high carboxylation efficiency even when stomata are partially closed during drought, conferring both water- and nitrogen-use advantages over C_3 counterparts.

Responses to Abiotic Stress

Under drought and heat stress, both C_3 and C_4 metabolic networks undergo reprogramming to mitigate cellular damage and maintain carbon assimilation. Li, Zhang, and Shi show that elevated CO_2 can partially offset drought-induced stomatal closure in C_3 species by maintaining higher intercellular CO_2 concentrations, leading to increased allocation of carbon to roots for osmoprotectant synthesis and enhanced soil carbon inputs via root exudates (Li, Zhang, and Shi). In contrast, Datta et al. report that C_4 species, though less stimulated directly by CO_2 enrichment, shift flux through alternative pathways under heat stress—up-regulating enzymes involved in reactive oxygen species scavenging and thermal tolerance, such as heat-shock proteins and antioxidant cycles—thereby preserving photosynthetic apparatus integrity (Datta et al.). Both pathways augment production of compatible solutes (e.g., proline, glycine betaine) that stabilize proteins and membranes. Network-model analyses further indicate that under combined heat and drought, C_4 plants sustain higher ATP-to-NADPH ratios and redirect excess reducing power into photoprotective cycles, enabling continued carbon fixation when C_3 photosynthesis becomes photo-inhibitory. These metabolic flexibilities underpin the superior resilience of C_4 taxa in arid and semi-arid climates.

IV. IMPACT OF CLIMATE CHANGE VARIABLES

Elevated CO_2 effects

Rising atmospheric CO_2 concentrations directly influence photosynthetic carbon gain in both C_3 and C_4 plants, but the magnitudes differ sharply. C_3 species, which are limited by Rubisco's affinity for CO_2 and prone to photorespiration, typically experience 20–30 percent increases in net primary production (NPP) when CO_2 levels rise from 400 ppm to 600–700 ppm (Keenan et al.). Elevated CO_2 reduces the oxygenation reaction of Rubisco, thereby curbing photorespiration and boosting water-use efficiency in C_3 canopies. In long-term field experiments, temperate grasslands dominated by C_3 grasses maintained 15–25 percent greater annual NPP under CO_2 enrichment, even during drought years when stomatal closure would otherwise inhibit assimilation (Keenan et al.).

C_4 plants, by contrast, possess a biochemical CO_2-concentrating mechanism that nearly saturates Rubisco at current ambient levels; as a result, they show modest NPP gains often under 10 percent under similar CO_2 enrichments (Liu, Chen, and Wang). Nevertheless, Liu, Chen, and Wang argue that even small biomass increases in C_4-dominated ecosystems can translate into significant carbon stocks when scaled across millions of hectares of grassland and savanna (Liu, Chen, and Wang).

Longer-term CO_2 enrichment triggers acclimation in C_3 species: leaf Rubisco content declines by up to 20 percent, nitrogen is reallocated from photosynthetic proteins to storage pools, and photosynthetic gains plateau after several years (Liu, Chen, and Wang). Nutrient availability further modulates these responses: phosphorus- or nitrogen-poor soils limit the capacity for sustained photosynthetic up-regulation by constraining protein synthesis necessary for Calvin-cycle enzymes (Liu, Chen, and Wang). Consequently, maximizing C_3 carbon sinks under elevated CO_2 requires parallel nutrient management to forestall down-regulation and maintain high NPP gains.

Temperature increases

Global warming shifts the thermal optima of photosynthetic pathways, favoring C_4 species in many regions. C_3 photosynthesis peaks at 20–25 °C, whereas C_4 photosynthesis remains efficient up to 35–40 °C due to reduced photorespiration and specialized leaf anatomy (Taylor et al.). Taylor et al. found that under constant light and 35 °C, C_4 grasses exhibited 15–20 percent higher assimilation rates than co-occurring C_3 grasses, which saw steep photorespiratory losses and declining net photosynthesis. In midlatitude dryland steppes, heatwaves exceeding 5 °C above seasonal norms curtailed C_3 grass NPP by 30 percent, while C_4 grasses maintained assimilation rates within 5 percent of baseline (Havrilla et al.).

The C_4 advantage under warming is compounded by improved water-use efficiency at elevated temperatures, as C_4 stomata can remain more closed for a given assimilation rate, reducing transpirational cooling demands and conserving soil moisture. As climate projections indicate more frequent high-temperature extremes, C_4 taxa are poised to expand into areas where C_3 performance declines, altering ecosystem carbon flux dynamics.

Water availability & drought

Differential drought resilience further distinguishes C_3 and C_4 carbon sequestration potentials. C_4 plants achieve up to 50 percent greater intrinsic water-use efficiency than C_3 species, owing to higher CO_2 assimilation per unit of stomatal conductance. Li, Zhang, and Shi report that under drought, C_3 plants partially compensate by closing stomata less when CO_2 is elevated—allocating more carbon to root growth and osmoprotectant production—but still suffer pronounced declines in above-ground biomass (Li, Zhang, and Shi). Keenan et al. observed that C_4- dominated grasslands sustained positive net ecosystem exchange (NEE) through multi-year drought cycles, as deep-rooting C_4 taxa accessed residual soil moisture and maintained photosynthesis when C_3 productivity collapsed.

Drought-induced shifts in carbon allocation also affect soil retention. While C_3 species increase root-derived carbon inputs during episodic stress, leaf senescence and lower litter quality limit long-term soil carbon stabilization. Conversely, C_4 litter is richer in structural carbohydrates and decomposes more slowly, contributing to persistent soil organic matter accumulation even under water scarcity.

Global distribution modelling

Climate-vegetation models project significant poleward and altitudinal shifts in C_4 biome extent under warming and CO_2 enrichment. Wang et al. (2024) combined observational datasets with optimality theory to map current global C_4 distributions and forecast future expansions by 2100 under high-emission scenarios. Their results suggest a poleward migration of C_4 grasses by 4–6 degrees latitude in both hemispheres, driven primarily by rising mean annual temperatures surpassing C_3 thermal thresholds (Wang et al. 2024). Metabolic network analyses further indicate that C_4 taxa preserve high assimilation efficiencies across varying soil nutrient statuses, facilitating their establishment in emerging warm-temperate zones (Wang et al.). These projected expansions could augment the global carbon sink by enlarging the spatial footprint of high-efficiency photosynthesis, although actual distribution shifts will hinge on water availability, land-use constraints, and competitive interactions.

By elucidating how elevated CO_2, temperature, and drought differentially affect C_3 and C_4 photosynthetic pathways, these studies inform land-management strategies—such as prioritizing C_4 bioenergy crops in warming regions and optimizing mixed-species plantings to maximize carbon sequestration under future climate change.

V. METHODOLOGICAL APPROACHES TO QUANTIFICATION

Field-based flux measurements

Quantifying ecosystem carbon exchange requires direct measurement of CO_2 fluxes between vegetation and the atmosphere. The eddy-covariance (EC) technique, employing high-frequency anemometers and infrared gas analyzers atop flux towers, captures turbulent vertical transport of CO_2, water vapor, and energy over footprints of 1–3 km^2. By correlating instantaneous vertical wind velocity with CO_2 concentration fluctuations, EC resolves net ecosystem exchange (NEE) at half-hourly intervals, allowing partitioning into gross primary production and ecosystem respiration (Ciais and Friend). To complement tower data at finer spatial scales or under heterogeneous canopy cover, static or automated chamber methods enclose soil or individual plants in transparent chambers, measuring flux by observing CO_2 concentration change over minutes; this approach is especially useful for isolating soil respiration and above-ground assimilation in both C_3 and C_4 grasses (IPCC 2022). Combining EC and chamber measurements enables scaling leaf- and soil-level processes to whole-ecosystem carbon budgets, while gap-filling algorithms and environmental covariates improve data continuity in periods of instrument downtime or extreme weather.

Remote sensing & GIS

Satellite-based remote sensing provides spatially explicit, repeatable estimates of vegetation cover, photosynthetic activity, and land-use change critical for assessing sequestration across broad regions. Multispectral sensors (e.g., MODIS, Landsat) yield vegetation indices such as NDVI and EVI, which correlate with leaf area index and canopy photosynthesis. High-albedo species, often among C_4 grasses or engineered cultivars, can be identified via short-wave reflectance patterns; mapping their distribution informs surface energy-balance models and potential albedo-driven cooling effects (IPCC 2021). Geographic Information Systems (GIS) integrate satellite imagery with climate layers, soil maps, and topography to delineate current C_3 vs. C_4 biomes and project land-cover shifts under warming scenarios. Zhang, Kumar, and Li demonstrate how combining high-resolution spectral data with machine-learning classification can accurately differentiate C_3 and C_4 stands, enabling dynamic monitoring of grassland composition and associated carbon pools (Zhang, Kumar, and Li).

Metabolic & network modelling

At the cellular level, genome-scale metabolic models (GEMs) reconstruct complete networks of enzymatic reactions, allowing simulation of carbon flux through C_3 and C_4 photosynthetic pathways under diverse environmental constraints. Wang et al. used GEMs to compare flux distributions in model C_3 (e.g., Arabidopsis) and C_4 (e.g., maize) species, revealing key bottlenecks in RuBP regeneration and energy balance that govern carbon assimilation efficiency (Wang et al.). By incorporating thermodynamic constraints and enzyme kinetics, these models predict how perturbations—such as elevated CO_2, temperature shifts, or nutrient limitation—reroute carbon through alternative pathways (e.g., photorespiration in C_3 or malate shuttling in C_4). Integrating GEM outputs with ecosystem-scale models bridges the gap between cellular biochemistry and landscape carbon budgets, offering mechanistic insights to guide crop engineering and land-VI. Synthesis, Implications & Future Directions

Comparative Sequestration Potentials by Biome

Temperate grasslands and croplands, largely dominated by C_3 species, exhibit strong seasonal carbon uptake during spring and autumn but become limited by heat and drought in midsummer (Still et al.). In these regions, C_3 photosynthesis benefits from elevated CO_2 that suppresses photorespiration, yet soil carbon inputs can be variable due to seasonal senescence. By contrast, tropical and subtropical savannas where C_4 grasses prevail maintain high carbon assimilation rates deep into the dry season owing to superior water-use efficiency and heat tolerance (Still et al.). Moreover, arid-zone shrub encroachment into former C_4 grasslands has shifted carbon inputs to deeper soil horizons via woody roots and recalcitrant litter, yielding net gains in long-term storage despite increased fire frequency (Walter and Smith). Together, these findings suggest that biome context temperature regime, moisture availability, and vegetation structure critically shapes the relative sequestration potentials of C_3 and C_4 pathways.

Land-management and Policy Implications

Optimizing carbon sinks under future climates requires region-specific strategies. In temperate zones, afforestation with fast-growing C_3 tree species can capitalize on elevated CO_2 to boost biomass stocks, but success hinges on nutrient management to prevent photosynthetic down-regulation (IPCC 2022). In warmer, water-limited areas, deploying C_4 bioenergy crops such as miscanthus or switchgrass offers dual benefits of high sequestration efficiency and renewable energy production, while minimizing irrigation demands (Kumar and Singh). Policymakers must therefore integrate land-use planning with climate projections, incentivizing C_3 afforestation where moisture and nutrients suffice, and C_4 grassland restoration or bioenergy cultivation where heat and drought prevail.

Research Gaps & Emerging Technologies

Despite advances, significant gaps remain in linking cellular mechanisms to landscape carbon budgets. Synthetic biology holds promise for transferring C_4 biochemical traits Kranz anatomy and CO_2 pumps into C_3 crops, potentially combining high CO_2-response with heat resilience (Melis and Ghirardi). Meanwhile, machine-learning algorithms can mine eddy-covariance and remote-sensing datasets to detect subtle patterns in carbon flux, improving model parameterization and upscaling accuracy (Datta et al.). Future work should focus on field trials of engineered C_3–C_4 hybrids, coupled with real-time data analytics, to validate sequestration gains and guide deployment at scale.

VI. CONCLUSION

This review demonstrates that C_3 plants, while highly responsive to elevated CO_2, are constrained by photorespiration and nutrient limitations, whereas C_4 species excel under high temperatures and drought due to their CO_2-concentrating mechanism and water-use efficiency. To maximize carbon-negative land uses, temperate regions may benefit from C_3 afforestation paired with nutrient management, while warmer, water-limited zones should prioritize C_4 bioenergy grasses. Moving forward, integrated approaches combining field flux measurements, high-resolution remote sensing, and mechanistic metabolic and distribution models are essential to accurately quantify sequestration across ecosystems and guide policy and land-management decisions under evolving climate conditions.

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