

# Forests, Plantations and Agroforestry as Green Shields for Climate-Resilient Food Production and Ecosystem Services: A Global Review

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## Abstract

Climate change poses significant threats to global food production, biodiversity, and ecosystem services. Nature-based solutions, particularly tree-based land-use systems such as forests, plantations, and agroforestry, play critical roles as “green shields” by mitigating climate impacts and enhancing resilience in agricultural landscapes. This review synthesizes recent global evidence on the multifunctional contributions of these systems to carbon sequestration, microclimate regulation, soil and water conservation, biodiversity support, and livelihood diversification. Forests, as the largest terrestrial carbon sinks, provide vital ecological stability and support food systems indirectly through ecosystem services. Plantations contribute substantially to carbon storage and rural livelihoods but face challenges related to biodiversity and water regulation, especially in monocultures. Agroforestry integrates trees with crops and livestock, offering a highly resilient land-use approach that improves food production, soil fertility, water management, and carbon capture while supporting diverse livelihoods. Comparative analyses underscore agroforestry’s unique balance of high carbon sequestration, biodiversity conservation, and direct food security benefits, positioning it as a versatile climate-resilient strategy. The review also highlights challenges such as land-use pressures, policy gaps, and monitoring complexities, and recommends stronger integration of green shields into national climate and food security policies through incentives, collaborative governance, and tailored management practices. Enhancing these systems’ effectiveness is essential for sustainable development and global climate adaptation and mitigation goals.

**Keywords:** Forests, Plantations, Agroforestry, Climate change, Food security, Ecosystem services, Green shields

## 1.0. Introduction

Climate change has become one of the most serious global concerns of the twenty-first century, exerting profound impacts on agricultural systems, ecosystem stability, and human livelihoods (IPCC, 2019). Global surface temperatures have increased significantly since the pre-industrial era, accompanied by shifts in rainfall patterns and a rise in the frequency and severity of extreme weather events including droughts, floods, and heat waves (IPCC, 2023). These climatic disturbances threaten food production, biodiversity, and the ecosystem services vital for human survival, with the greatest risks concentrated in regions already vulnerable to climate variability (FAO, 2022).

In light of these escalating challenges, nature-based solutions are increasingly emphasized as sustainable, cost-effective, and socially inclusive strategies for climate mitigation and adaptation. Among these, tree-based land-use systems—such as forests, plantations, and agroforestry—are particularly significant due to their multifunctional roles in carbon sequestration, microclimate regulation, soil and water conservation, and livelihood enhancement (Jose, 2009; Mbow et al., 2014; Bhol et al., 2024). These systems are progressively acknowledged as essential pillars of climate-resilient land management globally.

Collectively, forests, plantations, and agroforestry systems operate as “green shields,” protecting ecological and agricultural landscapes from climatic disturbances while supporting critical ecosystem services. Natural forests contribute to global and regional climate regulation through carbon storage and hydrological balance; plantations supply timber and non-timber resources while helping relieve pressure on native forests; and agroforestry integrates trees with crops and livestock to improve productivity, diversify household incomes, and strengthen resilience (Canadell and Raupach, 2008; Garrity et al., 2010; Chavan et al., 2015; Bhol and Parida, 2022; Bhol and Parida, 2024). By simultaneously supporting environmental stability and livelihood security, these “green shield” systems provide a comprehensive pathway toward sustainable development under changing climatic conditions.

This review consolidates global evidence to evaluate the contribution of forests, plantations, and agroforestry systems in enhancing climate-resilient food production and sustaining ecosystem services. It discusses their roles in mitigation and adaptation, analyzes region-specific and system-specific impacts, and identifies research gaps to support future scientific inquiry and policy formulation.

## 2.0. Materials and Methods

This review was developed through an extensive examination of peer-reviewed journal articles, global assessment reports, and reputable institutional documents pertaining to forests, plantations, agroforestry, climate change, ecosystem services, and food production. Relevant scientific literature was sourced from major academic databases such as Web of Science, Scopus, Google Scholar, and Research Gate using targeted keywords including green shields, forests and climate change, agroforestry and food security, plantations and ecosystem services, and climate-resilient agriculture (FAO, 2013; IPCC, 2019). In addition, reports and assessments from key international organizations, including FAO, IPCC, UNEP, and the Millennium Ecosystem Assessment, were reviewed (MEA, 2005).

Priority was given to publications from 2000 to 2025 to incorporate contemporary findings; however, foundational earlier studies were also included wherever necessary. Only literature published in English was considered. Collected sources were carefully screened to ensure relevance, and studies addressing carbon sequestration, climate adaptation strategies, food production enhancement, ecosystem service provision, and livelihood implications were synthesized qualitatively (Altieri et al., 2015). A comparative analytical approach was applied to assess how forests, plantations, and agroforestry systems function as green shields across diverse climatic contexts (Nair, 2011; Kumar et al., 2024; et al., 2016).

## 3.0. Results and Discussion

### 3.1. Concept of Green Shields in Climate Change Context

The concept of green shields refers to vegetation-based systems that safeguard ecosystems and human communities from the adverse impacts associated with climate change (Bonan, 2008). Tree-dominated landscapes function as protective barriers by influencing local microclimates, enhancing soil stability, regulating hydrological cycles, and capturing atmospheric carbon dioxide (Pan et al., 2011). In contrast to

purely engineered interventions, green shields provide a range of additional benefits such as supporting biodiversity, improving livelihoods, and sustaining vital ecosystem services (MEA, 2005; Pretty et al., 2018).

The term green shields refer to vegetation-based systems that protect landscapes and human societies from environmental stresses induced by climate change (Bonan, 2008). Tree-based systems act as buffers by moderating microclimates, stabilizing soils, regulating water flows, and sequestering atmospheric carbon dioxide (Pan et al., 2011). Unlike engineered solutions, green shields offer multiple co-benefits, including biodiversity conservation, livelihood enhancement, and ecosystem service provision (MEA, 2005; Pretty et al., 2018).

### 3.2. Role of Forests as Green Shields

#### 3.2.1 Carbon Sequestration and Climate Regulation

Forests function as the planet’s most significant terrestrial carbon reservoirs, storing vast quantities of carbon within vegetation and soils (Pan et al., 2011; Canadell and Raupach, 2008). Through the process of photosynthesis, they extract carbon dioxide from the atmosphere, thereby playing a central role in mitigating climate change (Bonan, 2008). Collectively, tropical, temperate, and boreal forests contribute to regulating the global carbon cycle and stabilizing climate systems (IPCC, 2023). The findings of several key studies are summarized in Table 1.

**Table 1. Role of Forests in Carbon Sequestration and Climate Regulation**

Aspect	Description	Climate Change Significance	References
Global Carbon Storage	Forests store carbon in aboveground biomass, belowground biomass, deadwood, litter, and soils	Largest terrestrial carbon reservoir; offsets anthropogenic CO <sub>2</sub> emissions	Pan et al. (2011); Canadell and Raupach (2008); FAO (2020)
Carbon Sequestration Mechanism	Atmospheric CO <sub>2</sub> is absorbed through photosynthesis and converted into plant biomass	Long-term climate change mitigation through biological carbon sinks	Bonan (2008); Malhi et al. (1999)
Forest Carbon Sink Strength	Global forests act as a persistent net carbon sink despite deforestation and disturbances	Slows accumulation of greenhouse gases in the atmosphere	Pan et al. (2011); Le Quéré et al. (2022)
Forest Biomes and Climate Regulation	Tropical, temperate, and boreal forests regulate global carbon and energy balances	Stabilizes global climate and moderates temperature extremes	IPCC (2023); Dixon et al. (1994)
Biophysical Climate Regulation	Forests influence albedo, evapotranspiration, cloud formation, and rainfall patterns	Regulates regional and global climate systems beyond carbon storage	Bonan (2008); Ellison et al. (2017)
Soil Carbon Dynamics	Forest soils store significant quantities of organic carbon, often exceeding biomass carbon	Enhances long-term carbon storage and ecosystem resilience	Canadell and Raupach (2008); Lal (2005)

Climate Feedbacks	Forest–climate interactions create positive and negative feedback mechanisms	Determines long-term effectiveness of forest-based mitigation	Bonan (2008); IPCC (2023); Ellison et al. (2017)
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Table 1 highlights the critical importance of forests in global carbon storage and climate moderation. Forest ecosystems capture atmospheric CO<sub>2</sub> via photosynthesis and retain it in aboveground and belowground biomass, litter, deadwood, and soils, serving as one of the most effective natural carbon sinks. Despite ongoing pressures such as deforestation and environmental disturbances, forests across the world continue to operate as net carbon sinks, thereby slowing the accumulation of greenhouse gases in the atmosphere.

Different forest types ranging from tropical to temperate and boreal systems play complementary roles in maintaining global carbon and energy balances, which helps stabilize climate patterns and reduce temperature extremes. Beyond carbon sequestration, forests exert strong biophysical influences by modifying surface albedo, enhancing evapotranspiration, and shaping precipitation dynamics, consequently regulating both regional and global climate systems. Additionally, forest soils store substantial amounts of organic carbon, contributing to long-term ecosystem stability and resilience. The intricate interactions between forests and the climate create multiple feedback mechanisms that ultimately determine the long-term potential of forest-based climate mitigation strategies, reinforcing their indispensable role in sustaining global climate stability.

### 3.2.2 Forests and Food Production

Forests contribute significantly to food production both directly and indirectly. They supply wild foods including fruits, nuts, honey, and other edible resources, while also supporting agricultural systems by sustaining pollinators, regulating water cycles, and moderating local climatic conditions essential for farming (Reed et al., 2017). Findings from various researchers on the role of forests in sustainable food systems are summarized in Table 2.

**Table 2. Role of Forests in Food Production and Food System Support**

Aspect	Description	Contribution to Food Production	References
Wild Food Resources	Forests provide edible fruits, nuts, seeds, leaves, tubers, mushrooms, insects, and bushmeat	Directly enhance food availability, dietary diversity, and nutrition for rural and indigenous communities	Reed et al. (2017); FAO (2016)
Non-Timber Forest Foods	Production of honey, resins, gums, and edible oils from forest species	Supports household food security and supplementary income	FAO (2016); Shackleton et al. (2011)
Pollinator Support	Forest habitats sustain wild pollinator populations essential for crop pollination	Improves yields and quality of pollinator-dependent crops	Garibaldi et al. (2013); Potts et al. (2016)
Water Regulation for Agriculture	Forests regulate streamflow, enhance groundwater recharge, and maintain watershed stability	Ensures water availability for rainfed and irrigated agriculture	Ellison et al. (2017); Calder (2007)

Microclimate Moderation	Forest cover moderates temperature, humidity, and wind patterns	Reduces heat and moisture stress on crops and farming systems	Bonan (2008); IPCC (2023)
Soil Fertility and Protection	Forest litter inputs and root systems reduce erosion and improve soil organic matter	Sustains long-term agricultural productivity in surrounding landscapes	Lal (2005); FAO (2015)
Landscape-Level Food Security	Forests stabilize agro-ecosystems and reduce vulnerability to climate extremes	Enhances resilience of food systems under climate variability	Reed et al. (2017); IPCC (2019)

Table 2 emphasizes the essential contribution of forests to enhancing food availability and strengthening food system resilience. Forest ecosystems provide a wide diversity of wild foods such as fruits, nuts, mushrooms, leaves, tubers, insects, and bush meat which play a vital role in improving dietary diversity, nutrition, and food security, particularly among rural and indigenous communities. In addition, non-timber forest products including honey, resins, gums, and edible oils not only supplement nutrition but also generate important household income.

Forests also maintain habitats for wild pollinators that are crucial for pollination of many agricultural crops, thereby increasing productivity and improving crop quality. By regulating stream flow, supporting groundwater recharge, and stabilizing watersheds, forests help secure reliable water supply for both irrigated and rainfed farming systems. Moreover, forest cover mitigates temperature extremes, reduces wind stress, and maintains humidity, thereby creating favourable microclimates for agriculture.

Forest litter and root systems enhance soil fertility by increasing organic matter and preventing erosion, contributing to sustained agricultural productivity in surrounding landscapes. At a broader scale, forests strengthen agro-ecosystem stability, reduce vulnerability to climatic shocks, and enhance the resilience of food systems under changing climate conditions (Reed et al., 2017; IPCC, 2019).

### 3.2.3 Ecosystem Services Provided by Forests

Forests deliver a wide spectrum of ecosystem services, including soil protection, water purification, flood moderation, biodiversity support, and cultural benefits (MEA, 2005). When forests are degraded, these essential services decline, thereby increasing vulnerability to climate impacts (FAO, 2018). Key findings from various studies are summarized in Table 3.

**Table 3. Ecosystem Services Provided by Forests**

Ecosystem Service Category	Description	Key Benefits	References
Carbon Sequestration and Storage	Forests absorb atmospheric CO <sub>2</sub> and store carbon in biomass and soils	Climate change mitigation and regulation of global carbon cycles	Pan et al. (2011); Canadell and Raupach (2008); IPCC (2023)
Climate Regulation	Forests influence temperature, rainfall, evapotranspiration, and atmospheric circulation	Moderation of local to global climate and buffering of extreme events	Bonan (2008); Ellison et al. (2017)

Water Regulation	Forests regulate hydrological processes including infiltration, groundwater recharge, and streamflow	Flood control, drought mitigation, and sustained water supply	Calder (2007); Ellison et al. (2017)
Soil Conservation and Fertility	Forest cover reduces erosion and enhances soil organic matter and nutrient cycling	Maintenance of soil productivity and land stability	Lal (2005); FAO (2015)
Biodiversity Conservation	Forests provide habitat for diverse flora and fauna	Maintenance of genetic resources and ecosystem resilience	Millennium Ecosystem Assessment (2005); IPBES (2019), Nayak et al. (2025)
Pollination Services	Forest habitats support wild pollinator populations	Enhanced crop pollination and agricultural productivity	Garibaldi et al. (2013); Potts et al. (2016), Mahapatra et al. (2025a)
Provisioning Services	Supply of timber, fuelwood, non-timber forest products, food, and medicinal resources	Livelihood support and food and nutritional security	FAO (2016); Shackleton et al. (2011)
Cultural and Recreational Services	Forests provide spiritual, recreational, aesthetic, and ecotourism values	Human well-being, mental health, and cultural identity	Millennium Ecosystem Assessment (2005); FAO (2018)
Regulating Natural Hazards	Forests stabilize slopes, reduce landslides, and buffer against floods and storms	Disaster risk reduction and landscape stability	IPCC (2019); Ellison et al. (2017)

Table 3 illustrates the extensive ecosystem services supplied by forests and highlights their indispensable contribution to environmental sustainability and human welfare. Forests function as major global carbon sinks by capturing atmospheric CO<sub>2</sub> and storing it within biomass and soils, playing a vital role in mitigating climate change. They further influence climate systems by regulating temperature, precipitation, and evapotranspiration, thereby helping to cushion the effects of extreme weather events. Forests are crucial in regulating water resources through improved infiltration, groundwater recharge, and streamflow management, which supports both flood control and drought resilience. They also enhance soil stability by reducing erosion and improving organic matter and nutrient cycling, thereby sustaining land productivity over the long term. Moreover, forests safeguard biodiversity by providing critical habitats for diverse species, thereby strengthening ecological resilience.

In addition, forests support pollination processes that are essential for agricultural production and supply a range of provisioning services such as timber, fuelwood, non-timber forest products, food, and medicinal resources, contributing significantly to livelihood security and nutrition. Cultural, recreational, and spiritual benefits further enhance quality of life, while the role of forests in mitigating natural hazards such as landslides and floods strengthens disaster risk reduction and landscape stability. Overall, the evidence

underscores forests as multifunctional ecological systems vital for sustainable development and climate resilience.

### 3.3. Plantations as Managed Green Shields

#### 3.3.1. Carbon Storage and Biomass Production by Plantations

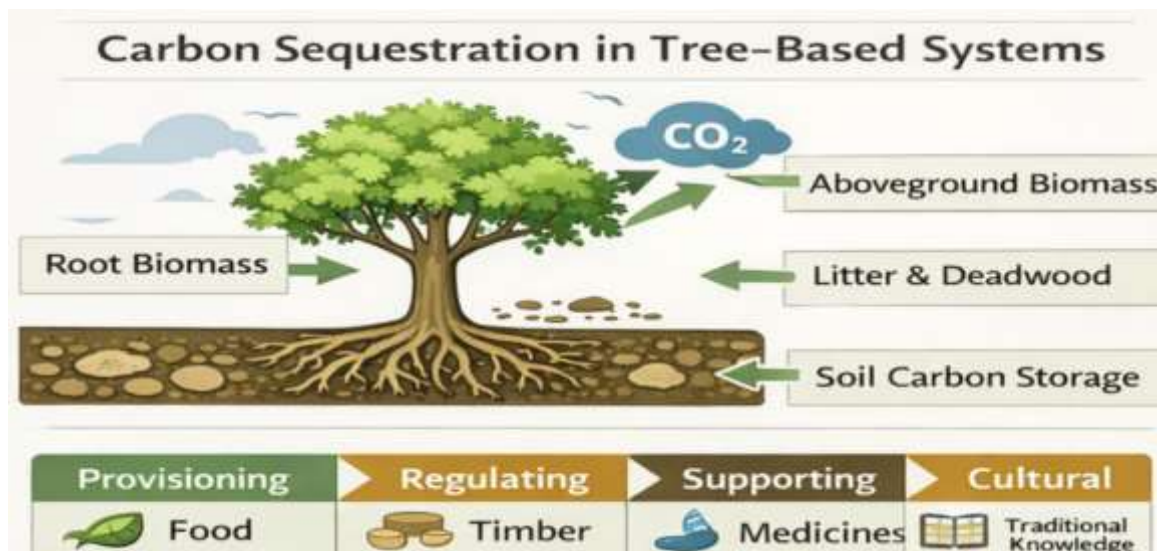
Properly managed plantation forests play a significant role in carbon sequestration while simultaneously supplying renewable raw materials, thereby easing extraction pressure on natural forest ecosystems (Zomer et al., 2016). Climate benefits are further enhanced when plantations incorporate mixed species and longer rotation cycles (Canadell and Raupach, 2008). A summary of research findings related to plantation-based carbon storage and biomass accumulation is presented in Table 4.

**Table 4. Carbon Storage and Biomass Production by Plantations**

Aspect	Description	Climate Change and Productivity Benefits	References
Aboveground Biomass Accumulation	Fast-growing plantation species accumulate substantial biomass within short rotations	Rapid carbon sequestration and enhanced wood productivity	Brown et al. (1997); FAO (2018)
Belowground Biomass and Root Carbon	Plantation root systems contribute carbon to soils through root turnover	Enhances long-term soil carbon storage and ecosystem stability	Jackson et al. (1996); Lal (2005)
Carbon Storage in Plantation Stands	Managed plantations store carbon in living biomass, litter, and harvested wood products	Offsets fossil fuel emissions and supports climate mitigation	Canadell and Raupach (2008); IPCC (2019)
High Biomass Productivity	Intensive management and improved genetics increase biomass yield per unit area	Higher carbon capture efficiency compared to unmanaged lands	Nair et al. (2009); FAO (2020)
Short-Rotation Plantations	Short-rotation forestry maximizes annual biomass production rates	Efficient carbon uptake and renewable bioenergy supply	Laclau et al. (2010); FAO (2018), Routray et al. (2018)
Harvested Wood Products	Carbon stored in long-lived wood products derived from plantations	Extends carbon storage beyond forest stands	IPCC (2019); Sathre and O'Connor (2010)
Reduced Pressure on Natural Forests	Plantation wood supply substitutes timber from natural forests	Indirect conservation of natural forest carbon stocks	Paquette and Messier (2010); FAO (2020)
Climate-Smart Plantation Management	Silvicultural practices optimize growth, carbon storage, and resilience	Enhances mitigation potential under changing climate conditions	Nabuurs et al. (2017); IPCC (2023); Bhol and Sinha (2006), Bhol et al. (2022a); Bhol et al. (2022b)

Table 4 and Figure 1 collectively demonstrate the crucial contribution of plantation systems to carbon storage and biomass generation, underscoring their relevance in climate change mitigation and productivity enhancement. Fast-growing plantation species are capable of accumulating substantial aboveground biomass within relatively short rotation periods, resulting in rapid carbon sequestration and high wood yield. Additionally, well-developed root systems significantly contribute to belowground biomass and soil carbon reserves, thereby improving long-term ecological stability.

Carbon is stored in managed plantations not only within live trees and forest litter but also through harvested wood products, which prolong carbon retention beyond the plantation landscape. Advances in genetic improvement and intensive silvicultural practices further boost biomass productivity, increasing carbon capture efficiency when compared with unmanaged lands. Short-rotation plantation systems enhance annual biomass accumulation, facilitating efficient carbon uptake and providing renewable bioenergy resources. Furthermore, the timber supplied by plantations helps reduce dependence on natural forests, indirectly supporting the conservation of their carbon stocks. Collectively, climate-smart plantation management strengthens resilience, promotes optimal growth, and maximizes carbon sequestration potential, reinforcing plantations as vital components of sustainable climate mitigation strategies.



**Fig 1. Pictorial depiction of carbon sequestration in tree-based systems**

Well-managed plantation forests store carbon not only in standing biomass and forest litter but also within harvested wood products, thereby prolonging carbon retention beyond the plantation boundary. Enhanced biomass production resulting from genetic improvement and intensive management practices significantly increases carbon sequestration efficiency compared to unmanaged landscapes. Short-rotation plantations further boost annual biomass accumulation, facilitating rapid carbon uptake while also supporting renewable bioenergy production. Additionally, by supplying timber that would otherwise be extracted from natural forests, plantations help safeguard existing forest carbon reserves. Collectively, climate-smart plantation management enhances productivity, resilience, and carbon storage capacity, reinforcing the vital role of plantations in sustainable climate change mitigation.

### 3.3.2. Role of plantations in Food and Livelihood Security

Plantation systems play an important role in strengthening rural livelihoods by providing income, fuelw-

ood, and industrial raw materials, thereby contributing indirectly to food security (Chavan et al., 2015). Key findings on this aspect are presented in Table 5.

**Table 5. Role of Plantations in Food and Livelihood Security**

Aspect	Description	Contribution to Food and Livelihood Security	References
Employment Generation	Plantation activities provide year-round and seasonal employment in planting, management, harvesting, and processing	Enhances rural employment and income stability	FAO (2020); Nair and Garrity (2012)
Income from Timber and Wood Products	Sale of timber, poles, pulpwood, and fuelwood from plantations	Provides reliable household income and market opportunities	Paquette and Messier (2010); FAO (2018)
Non-Timber Plantation Products	Production of fodder, honey, medicinal plants, resins, and gums within plantations	Diversifies income sources and supports subsistence needs	Shackleton et al. (2011); FAO (2016)
Energy and Fuelwood Supply	Plantations supply fuelwood and biomass energy	Reduces household energy insecurity and dependence on natural forests	FAO (2020); IPCC (2019)
Food Crop Integration (Agro-Plantation Systems)	Intercropping of food crops during early plantation stages	Enhances short-term food availability and farm income	Nair et al. (2009); Chavan et al. (2015)
Livestock Support	Plantations provide fodder, shade, and shelter for livestock	Improves livestock productivity and livelihood resilience	FAO (2016); Reed et al. (2017)
Market and Value Chain Development	Plantation-based industries promote rural enterprises and infrastructure	Strengthens local economies and livelihood diversification	FAO (2018); Paquette and Messier (2010)
Reduced Pressure on Natural Forests	Plantation wood supply substitutes extraction from natural forests	Sustains long-term ecosystem services that support food security	FAO (2020); IPBES (2019)

Table 5 demonstrates the crucial contribution of plantations to both food and livelihood security, especially in rural regions. Plantation development creates significant employment opportunities across planting, maintenance, harvesting, and processing stages, which enhances income stability and rural employment. Revenue generated from the sale of timber, pulpwood, poles, and fuelwood offers dependable household income and market opportunities, while non-timber plantation products such as fodder, honey, medicinal plants, resins, and gums diversify livelihood options and support subsistence requirements. Plantations also serve as a key source of household energy by providing biomass and fuelwood, thereby reducing reliance on natural forests. Integrating food crops during the initial phases of plantation

establishment improves short-term food availability and supplemental farm income. Furthermore, plantations support livestock by supplying fodder, shade, and shelter, contributing to improved animal productivity and livelihood resilience.

In addition, plantation-based industries stimulate market development, enhance value chains, and promote rural enterprise growth, strengthening local economies. By substituting timber extraction from natural forests, plantations help conserve natural ecosystems and sustain essential ecosystem services that underpin long-term food security and resilient livelihoods.

### 3.3.3. Environmental Concerns and Sustainability

Monoculture plantations may reduce biodiversity and water availability. Sustainable plantation management practices are therefore essential to maximize green shield benefits (FAO, 2022). Some reports on environmental and sustainability benefits by plantations are presented in Table 6.

**Table 6. Role of Plantations in Environmental Concerns and Sustainability**

Aspect	Description	Environmental and Sustainability Benefits	References
Soil Conservation and Rehabilitation	Plantations help control soil erosion, enhance soil structure, and rehabilitate degraded landscapes	Improves land productivity and prevents processes such as desertification	Lal (2005), Chavan et al. (2015)
Biodiversity Support	Incorporating mixed-species and native trees in plantations provides wildlife habitat and enhances biodiversity	Strengthens ecosystem resilience and supports conservation objectives	Paquette and Messier (2010), IPBES (2019)
Carbon Sequestration and Climate Mitigation	Plantations store carbon in biomass and soils, acting as significant carbon sinks	Reduces greenhouse gas concentrations and contributes to global climate mitigation goals	Canadell and Raupach (2008); IPCC (2023), Routray et al. (2018)
Water Cycle Regulation	Plantation systems influence hydrological processes by improving infiltration and reducing surface runoff	Promotes watershed stability and lowers flood risk	Calder (2007); Ellison et al. (2017)
Reduction of Pressure on Natural Forests	Plantation-based wood and non-timber production decreases reliance on natural forests	Supports conservation of primary forests and their ecosystem services	FAO (2020); Paquette and Messier (2010)
Sustainable Land Use and Productivity	When scientifically managed, plantations ensure efficient land use, reduce shifting cultivation, and sustain timber supply	Integrates economic benefits with ecological protection	Nabuurs et al. (2017); FAO (2018)
Pollution Mitigation and Soil Remediation	Specific plantation species are effective in phytoremediation and pollutant absorption	Enhances environmental quality by improving contaminated soils and water	Sao and Maru (2017); Kumar et al. (2024); Chavan et al. (2015)

Climate Resilience	Diversified plantation systems improve resistance to pests, diseases, and climatic stressors	Supports long-term sustainability of forest landscapes	Nabuurs et al. (2017); IPCC (2023)
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Table 6 clearly demonstrates that plantation systems play a crucial role in addressing key environmental challenges while advancing sustainability objectives. By minimizing soil erosion, restoring degraded lands, and improving soil health, plantations contribute significantly to long-term land productivity. Incorporating diverse and native tree species further enhances biodiversity and promotes ecosystem stability.

In addition, plantations substantially support climate change mitigation through enhanced carbon storage in both biomass and soils, thereby helping to reduce greenhouse gas emissions. Their positive influence on hydrological processes—such as increased infiltration and lower runoff—also strengthens watershed management and reduces flooding risks. By providing sustainable supplies of timber and non-timber forest products, plantations help relieve harvesting pressure on natural forests, thereby aiding in the preservation of primary forest ecosystems.

When effectively managed, plantations foster sustainable land use, aligning productivity with environmental stewardship. Moreover, several plantation species contribute to pollution control through phytoremediation, improving the quality of degraded soils and water bodies. Overall, diverse, well-managed plantation systems enhance climate resilience and play a vital role in promoting environmentally sustainable land management.

### 3.4. Agroforestry as a Climate-Resilient Green Shield

#### 3.4.1 Contribution of Agroforestry to Food Production

Agroforestry significantly enhances farm productivity by supplying a wide range of products, including fruits, nuts, fodder, fuelwood, and timber, while also helping stabilize crop yields under changing climatic conditions (Garrity et al., 2010). Numerous studies have documented these benefits, and the contributions reported by selected researchers are summarized in Table 7.

**Table 7. Role of Agroforestry Systems in Food Production**

Aspect	Description	Contribution to Food Production	References
Diversified Food Sources	Integration of trees with crops and livestock supplies fruits, nuts, vegetables, fodder, and livestock products	Improves dietary diversity, nutritional security, and overall food availability	Garrity et al. (2010); FAO (2016)
Improved Crop Yields	Tree components enhance microclimate, soil fertility, and moisture retention	Leads to higher and more stable crop yields under climate variability	Jose (2009); Nair et al. (2009)
Livestock Support	Trees provide feed resources, shade, and protection	Promotes better livestock health and productivity	Reed et al. (2017); FAO (2016)

Soil Fertility Enhancement	Nitrogen-fixing species and organic matter inputs enrich soil nutrients	Maintains long-term soil productivity	Garrity et al. (2010); Lal (2005)
Pollinator Habitat	Trees create supportive environments for pollinators	Enhances pollination services vital for food crop production	Garibaldi et al. (2013); Potts et al. (2016); Mahapatra et al. (2025b)
Risk Diversification	Production of multiple outputs reduces reliance on monocropping	Strengthens resilience against climatic stresses, pests, and diseases	Lin (2011); Roshetko et al. (2007)
Water Regulation	Tree cover improves infiltration and moderates evapotranspiration	Increases water availability for crops, particularly during dry periods	Ellison et al. (2017); Calder (2007)

Table 7 clearly demonstrates that agroforestry systems play a vital role in strengthening food production and enhancing the resilience of agricultural systems. The integration of trees with crops and livestock ensures a steady supply of diversified food products, contributing to improved nutrition and food security. Yield improvements arise from enhanced microclimatic conditions, increased soil fertility, and better water retention capacity, which collectively support stable production even under climate stress. Furthermore, agroforestry enhances livestock productivity by supplying fodder and providing thermal comfort through shade and shelter. The incorporation of nitrogen-fixing trees and organic matter inputs sustains soil health, ensuring long-term agricultural sustainability. Tree-based landscapes also foster habitats for pollinators, thereby supporting essential pollination services for many key food crops. Overall, agroforestry reduces production risks, improves water regulation, and increases system resilience, highlighting its crucial role in sustainable and climate-resilient food production systems (Fig. 2).



**Fig 2. A schematic view of agroforestry for food and livelihoods**

### 3.4.2 Ecosystem Services of Agroforestry

Agroforestry systems substantially enhance ecosystem functioning by supporting biodiversity, enhancing carbon sequestration, improving nutrient cycling, and strengthening pollination services, thereby contributing to sustainable agricultural landscapes (Montagnini and Nair, 2004; Verchot et al., 2007). Trees integrated into these systems play a significant role in atmospheric carbon capture (Bhol et al., 2024). For instance, mature poplar trees can sequester about 266 kg of carbon, whereas green ash and white spruce store approximately 63 kg and 143 kg, respectively. Belowground carbon stored in roots, which may constitute 50–75% of aboveground storage levels, also represents a major contribution to climate mitigation. Carbon sequestration potential reported for different agroforestry systems in India is summarized in Table 8.

**Table 8. Carbon sequestration in different agroforestry systems in India**

S. No.	Agro-climatic zones	Agroforestry system	Carbon sequestration potential (Mg C ha <sup>-1</sup> year <sup>-1</sup> )	References
1	Western Himalayan Region	Agri-horticulture (Prunus armeniaca + Ocimum sanctum)	1.80	Handa et al. (2020)
		(Prunus persica + Ocimum sanctum)	2.0	
2	Eastern Himalayan Region	Silvipasture (Morus alba + Setaria anceps grass)	1.55	Handa et al. (2020)
3	Lower Gangetic Plains Region	Agrisilviculture (Eucalyptus tereticornis + rice-wheat)	10.7	Sirohi and Bnagrawa (2017)
4	Middle Gangetic Plains Region	Agrisilviculture (Tectona grandis + sorghum/groundnut)	2.32	Handa et al. (2020)
5	Upper Gangetic Plains Region	Agrisilviculture (Dalbergia sissoo + mustard)	2.83	Newaj et al. (2012)
6	Trans-Gangetic Plains Region	Agrisilviculture (Populus deltoides + wheat/potato/turmeric)	9.12	Chavan et al. (2022)
7	Eastern Plateau and Hills Region	Agrisilviculture (Albizia procera + wheat)	5.70	Newaj et al. (2012)
8	Central Plateau and Hill Region	Agrisilviculture (Acacia + greengram-mustard)	3.70	Newaj et al. (2008)
9	Western Plateau and Hills Region	Agrisilviculture (Ailanthus excelsa + cowpea-mustard)	9.64	Handa et al. (2019, 2020)

10	Southern Plateau and Hills Region	Silvipasture (Leucaena leucocephala + Gliricidia sepium + Stylosanthes hamata)	23.2	Handa et al. (2019)
11	East Coast Plains and Hills Region	Hortisilviculture (Acacia mangium + pineapple)	5.51	Handa et al. (2019)
12	Western Dry Region	Silvipasture (Ailanthus + Cenchrus ciliaris/Panicum antidotale)	9.64	Handa et al. (2020)
13	Island Regions	Hortipasture (Cocos nucifera + Calliandra calothyrsus)	3.50	Joy et al. (2019)

Table 8 demonstrates substantial variation in carbon sequestration across agroforestry systems in different Indian agro-climatic regions, largely determined by species composition, system design, and regional environmental conditions. Silvipasture systems showed the highest sequestration potential, particularly in the Southern Plateau and Hills region (23.2 Mg C ha<sup>-1</sup> year<sup>-1</sup>), owing to high biomass accumulation from diverse tree–forage combinations. Agrisilviculture systems in the Lower Gangetic Plains and Western Plateau and Hills regions also recorded high sequestration levels (>9 Mg C ha<sup>-1</sup> year<sup>-1</sup>), reflecting favorable growth environments and inclusion of fast-growing species.

Conversely, agroforestry systems in the Himalayan regions recorded comparatively lower values (1.55–2.0 Mg C ha<sup>-1</sup> year<sup>-1</sup>), which may be attributed to lower temperatures and shorter growing periods. Overall, the findings clearly indicate that regionally adapted agroforestry models, particularly silvipasture and efficiently managed agrisilviculture systems, can make a significant contribution to carbon storage and climate change mitigation in Indian agricultural landscapes.

A diverse array of agroforestry systems and practices is implemented worldwide, each contributing significantly to environmental sustainability. Beyond their recognized role in carbon sequestration, agroforestry systems deliver numerous additional ecosystem services, as highlighted by various researchers and summarized in Table 9.

**Table 9. Role of Agroforestry Systems in Ecosystem Services**

Ecosystem Service Category	Description	Contribution by Agroforestry Systems	References
Carbon Sequestration and Storage	Trees and soils within agroforestry landscapes store considerable carbon	Helps mitigate climate change while improving agricultural carbon reserves	Mbow et al. (2014); Nair et al. (2009)
Soil Fertility and Nutrient Cycling	Organic inputs and nitrogen-fixing trees enhance soil nutrients and structure	Improves soil quality and sustains long-term agricultural productivity	Garrity et al. (2010); Lal (2005), Bhol et al. 2020

Water Regulation	Roots improve infiltration while reducing runoff and erosion	Strengthens watershed stability and conserves water resources	Ellison et al. (2017); Calder (2007)
Biodiversity Conservation	Agroforestry provides habitats and ecological corridors	Enhances species diversity and ecosystem resilience	Tscharntke et al. (2011); IPBES (2019)
Pollination Services	Tree cover supports pollinator diversity and nesting	Sustains crop pollination and ecological functioning	Garibaldi et al. (2013); Potts et al. (2016), Mahapatra et al. 2025a; Mahapatra et al. 2025b
Microclimate Moderation	Trees influence farm temperature and humidity	Lowers heat stress and improves growing conditions	Jose (2009); Lin (2011)
Erosion Control	Tree cover protects soil and stabilizes landscapes	Prevents land degradation and maintains productivity	Lal (2005); Chavan et al. (2015)
Provisioning Services	Agroforestry supplies timber, fruits, fodder, medicines, and fuelwood	Diversifies livelihood options and supports household needs	FAO (2016); Shackleton et al. (2011)

Table 9 demonstrates the multifunctional nature of agroforestry in supporting sustainable and climate-resilient agriculture. By incorporating trees into farming landscapes, agroforestry systems enhance both above- and below-ground carbon storage, thereby contributing to climate change mitigation. Improvements in soil fertility through nutrient enrichment and organic matter inputs strengthen long-term soil productivity. Enhanced water regulation through better infiltration and reduced runoff helps maintain watershed health and reduces flood risks.

Agroforestry also contributes significantly to biodiversity conservation by offering habitats and ecological linkages, which support beneficial species, including pollinators that are essential for crop productivity. Additionally, tree cover moderates the farm microclimate, mitigates heat and moisture stress, and plays a vital role in erosion control. Alongside regulating and supporting services, agroforestry systems provide vital provisioning benefits such as timber, fruits, fodder, and fuelwood, thereby enhancing livelihood security. Collectively, these findings highlight agroforestry as an integrated land-use system capable of simultaneously improving ecosystem services, strengthening food systems, and supporting rural livelihoods.

### 3.5. Comparative Role of Forests, Plantations and Agroforestry

The potential contributions of forests, plantations, and agroforestry systems as green shields for climate-resilient food production and ecosystem services vary distinctly. A summarized comparison of their roles is presented in Table 10.

**Table 10. Comparative Role of Forests, Plantations, and Agroforestry as Green Shields for Food Production and Ecosystem Services**

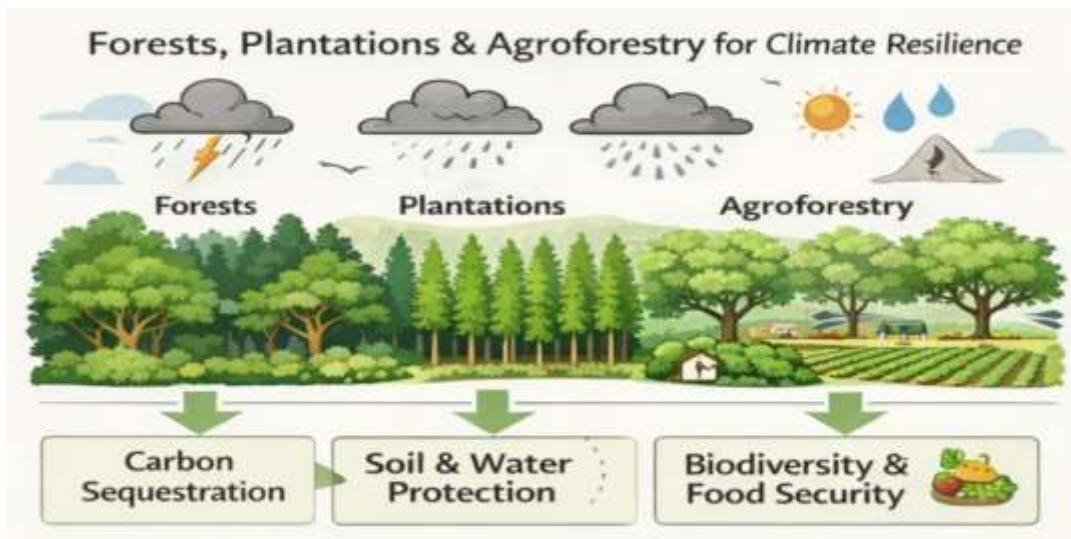
Component	Forests	Plantations	Agroforestry
Carbon sequestration	Very high (Pan et al., 2011)	High (Zomer et al., 2016)	High (Albrecht and Kandji, 2003)
Biodiversity support	Very high (MEA, 2005)	Moderate (FAO, 2022)	High (Jose, 2009)
Food production support	Indirect (Reed et al., 2017)	Indirect (Chavan et al., 2015)	Direct and indirect (Garrity et al., 2010)
Climate resilience	High (IPCC, 2019)	Moderate (FAO, 2022)	Very high (Altieri et al., 2015)
Ecosystem services	Multiple (MEA, 2005)	Limited to moderate (FAO, 2022)	Multiple (Jose, 2009)

Table 10 underscores the complementary yet distinct functions of these three tree-based systems in supporting food production and ecosystem services under climate stress. Forests lead in carbon storage and biodiversity conservation due to their complex ecosystems and sustained biomass accumulation, reinforcing their vital role in climate change mitigation and ecological balance (Pan et al., 2011; MEA, 2005). Plantations, while offering considerable carbon sequestration benefits, tend to support less biodiversity and a narrower suite of ecosystem services, especially when dominated by monoculture species (FAO, 2022).

In contrast, agroforestry stands out as the most versatile land-use system, combining substantial carbon sequestration with robust biodiversity conservation and both direct and indirect support for food production (Jose, 2009; Garrity et al., 2010). The integrated nature of agroforestry enhances resilience to climatic variability by moderating environmental extremes and improving soil and water dynamics (Altieri et al., 2015). Thus, although forests remain crucial for conservation and global climate regulation, agroforestry presents a highly resilient, multifunctional green shield ideal for sustaining food security and ecosystem services in a changing climate.

### 3.6 Effectiveness of Forests, Plantations, and Agroforestry as Green Shields

Extensive global research confirms that forests, plantations, and agroforestry systems each contribute significantly, though in different ways, to enhancing climate resilience and supporting food production (see Fig. 3). Forests serve as major carbon reservoirs and harbor rich biodiversity, playing a critical role in regulating climate and water cycles that indirectly support agricultural productivity and ecosystem functions (Pan et al., 2011; Bonan, 2008). However, ongoing deforestation and forest degradation undermine these functions, threatening the sustainability of their protective roles (FAO, 2022).



**Fig 3. An illustration of forests, plantations and agroforestry for climate resilience**

Plantations, especially those employing mixed-species compositions and extended rotation periods, significantly contribute to carbon sequestration while providing essential products such as fuelwood and timber. This supply helps reduce harvesting pressures on natural forests (Zomer et al., 2016). However, monoculture plantations, if not managed with sustainability in mind, can negatively impact biodiversity and disrupt local water cycles (FAO, 2018).

Agroforestry stands out as a robust climate-resilient land management approach by integrating trees with crops, thereby stabilizing crop yields under climate stress, improving soil fertility, conserving water resources, and boosting carbon sequestration (Jose, 2009; Garrity et al., 2010). The diverse range of products derived from agroforestry supports varied livelihoods, which is crucial for ensuring food security amid the uncertainties of a changing climate (Altieri et al., 2015).

### 3.7 Climate Resilience and Food Security

Agroforestry and forest ecosystems play a crucial role in mitigating climate extremes by moderating temperature fluctuations, enhancing soil moisture retention, and lowering the risks associated with droughts and floods (Mbow et al., 2014; Nair, 2011). Research from regions in Asia and Africa indicates that smallholder farmers who implement agroforestry practices tend to experience greater stability in crop yields and benefit from diversified income sources, which collectively help reduce the risk of food insecurity (Kumar et al., 2024 et al.; Pretty et al., 2018).

While plantations support food security mainly by providing livelihood opportunities and non-food resources, their contribution is generally less direct compared to that of agroforestry systems and natural forests (Chavan et al., 2015). The effectiveness of plantations as green shields can be enhanced through sustainable forest management policies that balance biodiversity conservation with the needs of local communities (IPCC, 2019).

### 3.8 Ecosystem Services and Biodiversity Conservation

Forests deliver the most extensive array of ecosystem services, encompassing cultural and supporting functions essential for maintaining biodiversity and pollination processes that are fundamental to agricultural productivity (MEA, 2005; Reed et al., 2017). In contrast, plantations generally provide moderate levels of regulating and provisioning services but often lack significant cultural values (FAO, 2022). Agroforestry systems, on the other hand, offer a broad spectrum of services similar to those of

forests, such as supporting diverse biological communities and enhancing nutrient cycling, which are vital for maintaining ecological stability at the landscape scale (Jose, 2009; Bhol et al., 2024).

#### **4.0 Challenges and Limitations**

Despite their numerous benefits, the development and upkeep of green shields face multiple obstacles including pressures from land-use changes, insufficient policy frameworks, lack of adequate incentives, and limited awareness among farmers (Chavan et al., 2015; FAO, 2018). Monoculture plantations may elevate risks related to pests and diseases, while agroforestry systems that are poorly designed may lead to competition between trees and crops for resources if species selection is not carefully managed (Zomer et al., 2016).

Furthermore, monitoring and accurately quantifying carbon sequestration along with other ecosystem services is challenging due to spatial variability and differing methodologies, which hinders the consistent application of supportive policies (Smith et al., 2014). To maximize the potential of these systems for climate adaptation and mitigation, increased region-specific research and capacity development are essential.

#### **5.0 Future Perspectives and Policy Recommendations**

Enhancing the effectiveness of green shields demands their incorporation into national frameworks addressing climate change adaptation and food security. This integration should be bolstered by supportive measures such as payments for ecosystem services, subsidies for agroforestry practices, and provision of technical support (FAO, 2018; IPCC, 2023). Effective and sustainable landscape management hinges on cooperative governance that brings together local communities, governmental bodies, and scientific stakeholders (Pretty et al., 2018).

Advances in selecting appropriate species, refining silvicultural techniques, and designing agroforestry systems adapted to specific climatic and socio-economic conditions are key to boosting resilience and productivity (Altieri et al., 2015; Mbow et al., 2014). Additionally, enhancing data accessibility and standardizing monitoring protocols for carbon storage and ecosystem services will improve the integration and valuation of green shields within climate and agricultural policy frameworks (Smith et al., 2014).

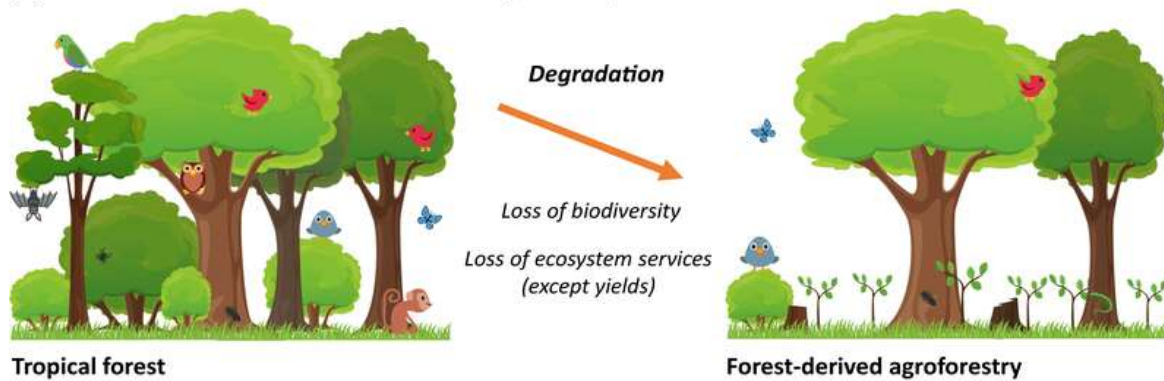
#### **6.0 Policy Implications and Future Perspectives**

The inclusion of forests, plantations, and agroforestry systems in national climate policies, food security initiatives, and land management strategies is critical for sustainable development (FAO, 2018; IPCC, 2023). Providing incentives for afforestation, reforestation, and the adoption of agroforestry can significantly reinforce green shields across landscapes and regions (Chavan et al., 2015).

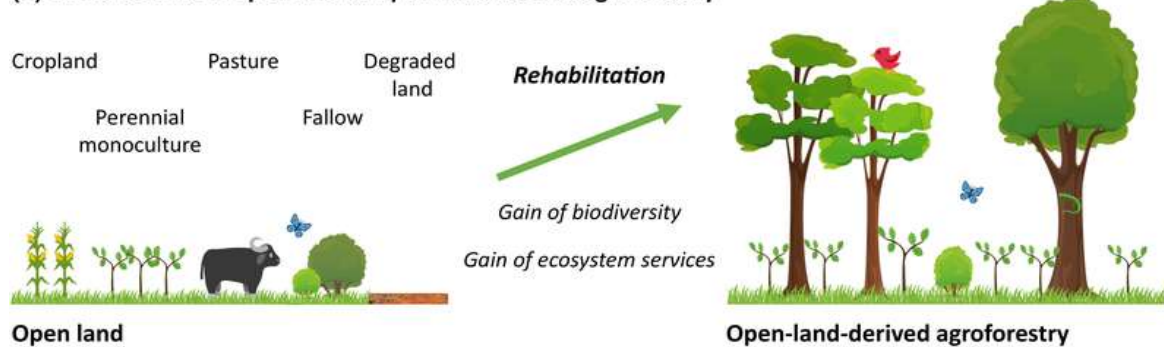
#### **7.0 Conclusion**

Forests, plantations, and agroforestry systems function as effective green shields that enhance climate-resilient food production and sustain ecosystem services (Jose, 2009; IPCC, 2019). Strengthening these systems through sustainable management and supportive policies is critical for addressing climate change challenges and achieving global sustainability goals (Pretty et al., 2018; Fig 4).

(a) Conversion from forest to forest-derived agroforestry



(b) Conversion from open land to open-land-derived agroforestry



**Fig 4. A summarised view of forests, plantations and agroforestry for climate-resilient food production and ecosystem services**

**Ethical Standards**

All authors declare that the submission is original, unpublished, and not under consideration elsewhere.

**Explanation of any issue relating to journal policies**

There is no issue relating to journal policies.

**Declaration of any competing interest**

There is no competing interest.

**Confirmation that all authors have approved the manuscript for submission**

All authors declare that they have approved the manuscript for submission.

**Data availability**

Data will be made available on request.

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