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Forests as Carbon Architects Shaping Climate Stability

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About 31% of the world's land area is covered by forests (FAO, 2020), which act as vital carbon sinks that have a significant impact on the Earth's climate system by controlling atmospheric concentrations of carbon dioxide, the main greenhouse gas causing anthropogenic climate change. Global warming and climatic patterns have become more unstable since the Industrial Revolution due to human activities like burning fossil fuels, deforestation and changing land use, which have caused atmospheric CO_2 concentrations to rise above 420 ppm (NOAA, 2024). Forests play an essential role in reducing climate change, as evidenced by international frameworks such as the Paris Agreement, REDD+ (Reducing Emissions from Deforestation and Forest Degradation) and various national carbon budgeting initiatives. Nature-based solutions, especially those that involve reforestation, forest conservation and sustainable land management, could account for as much as 30% of the global mitigation required to reach net-zero emissions by 2050, according to the Intergovernmental Panel on Climate Change (IPCC, 2022). In contrast to carbon capture and storage (CCS) and other engineered carbon capture technologies, forests offer a multitude of co-benefits, such as soil protection, water regulation, biodiversity conservation and socioeconomic support to millions of people, particularly in the Global South (Griscom *et al.*, 2017; Chazdon *et al.*, 2020). These multifaceted advantages are essential for adaptation, ecosystem resilience, human livelihoods and climate mitigation.

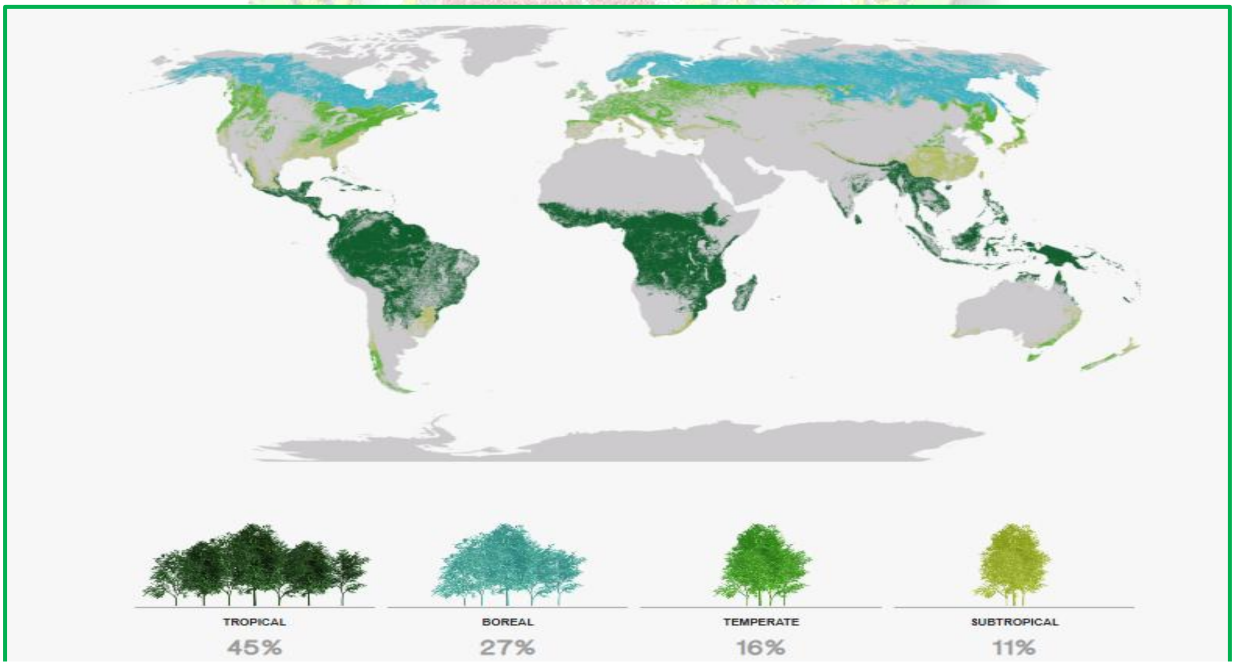


Fig.1: Proportion and distribution of global forest area by climatic domain, 2020 (FAO, 2020)

Carbon Sequestration: Photosynthesis, Biomass and Forest Dynamics

Photosynthesis, a biochemical process by which trees absorb CO_2 and transform it into organic carbon compounds that form the structural components of biomass, such as trunks, branches, roots and leaves, is at the heart of forests' ability to regulate the climate. The global carbon cycle is supported by this terrestrial carbon fixation. Forests act as long-term reservoirs and buffers against abrupt increases in atmospheric CO_2 because the carbon they store builds up over years to centuries. In a thorough worldwide analysis, Pan *et al.* (2011) showed that forests offset almost 30% of emissions from fossil fuels by absorbing about 2.4 ± 0.4 petagrams of carbon per year. This result validates previous findings by Canadell and Raupach (2008), who calculated that roughly one-third of anthropogenic CO_2 emissions per year are sequestered by terrestrial ecosystems, primarily forests.

Tropical forests are especially significant carbon sinks because of their year-round favorable climate, high levels of solar radiation and effective nutrient cycling. The Amazon and Congo Basin forests store the most carbon mass worldwide, according to Baccini *et al.* (2012)'s analysis of satellite-based biomass data. However, because of their longer tree lifespans and slower rates of decomposition, temperate and boreal forests make significant contributions to long-term carbon sequestration despite their lower productivity (Luyssaert *et al.*, 2008; Pregitzer & Euskirchen, 2004). Studies have shown that even mature forests continue to absorb carbon, defying previous beliefs that old-growth forests either become carbon neutral or emit carbon. For this reason, they must be protected and managed sustainably in order to meet climate goals (Krankina *et al.*, 2002; Nave *et al.*, 2011). The age, species composition, forest structure and disturbance history significantly influence sequestration rates (Pregitzer & Euskirchen, 2004; Keith *et al.*, 2009).

Dead organic matter, such as fallen branches and leaf litter, make up a significant carbon pool in addition to aboveground biomass. These materials slowly cycle through decomposition processes that return nutrients to the soil (Harmon *et al.*, 2004). These carbon stores are disrupted by anthropogenic (logging, fragmentation) or natural (fires, pests) forest disturbances, which change the dynamics of the forest and release CO_2 back into the atmosphere (Díaz-Yáñez *et al.*, 2022). Thus, to maximize the benefits of carbon sequestration, it is essential to comprehend forest ecology, including succession dynamics and regeneration.

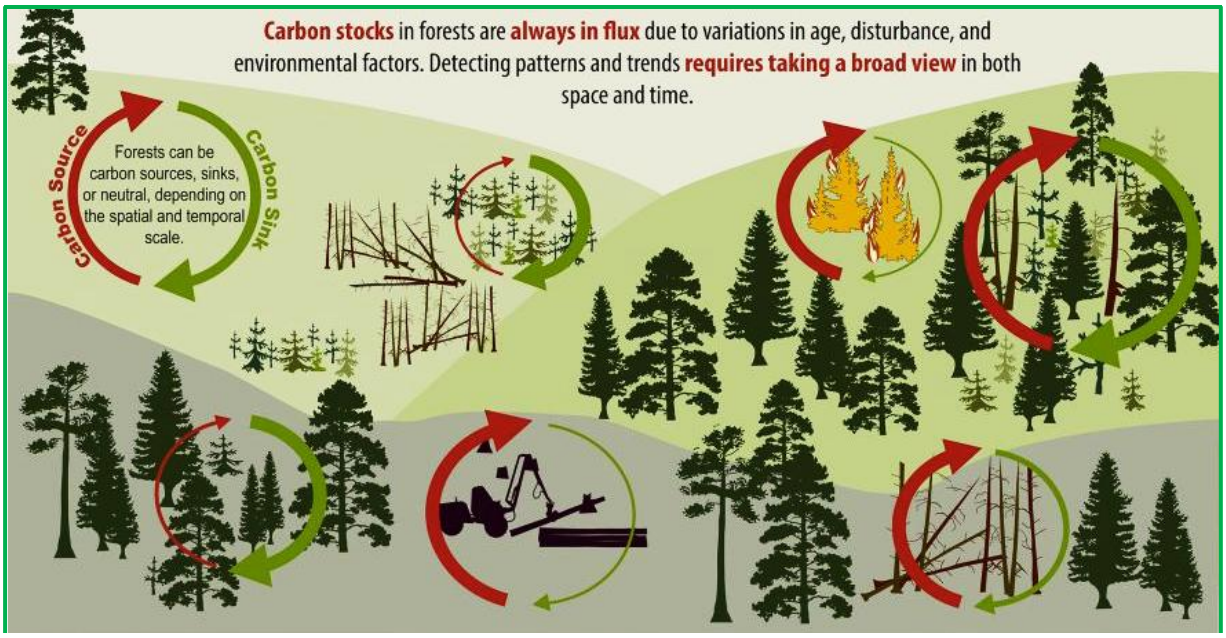


Fig.2: Illustration of carbon flow in a forest ecosystem (USDA, 2021)

Soil Carbon Storage and Belowground Carbon Dynamics

In addition to biomass, soils are the largest terrestrial carbon reservoir, holding about 1,500 gigatons of carbon, more than the combined amount of carbon in the atmosphere and vegetation (Lal, 2005; Jobbágy & Jackson, 2000). Through inputs like leaf litter, root turnover, microbial biomass and the production of stable humic substances, forest soils are able to store carbon. Physical protection within soil aggregates, chemical composition and environmental factors like moisture and temperature all affect how long soil organic carbon lasts (Schlesinger & Andrews, 2000; Lehmann & Kleber, 2015).

Slow decomposition rates caused by high moisture and low temperatures in boreal and montane forests lead to a substantial buildup of SOC, which helps regulate the climate over centennial timescales (Koven *et al.*, 2011; Post *et al.*, 1982). However, despite their high fertility, tropical forest soils frequently have lower SOC stocks because of the quick turnover of organic matter in warm, humid climates. Despite this, they are still very important for the short-term carbon cycle (Silver *et al.*, 2000). The potential of forest restoration for soil carbon recovery has been highlighted by empirical studies like Nave *et al.* (2010) and Laganière *et al.* (2010), which observed notable increases in soil carbon stocks after afforestation and reforestation, especially on formerly degraded or agricultural lands.

Root architecture and forest type also affect the vertical distribution of soil carbon. Because tree-dominated ecosystems have deeper rooting systems, which deposit carbon below the surface where it is less likely to be disturbed, Jobbágy and Jackson (2000) showed that these ecosystems store more carbon at greater soil depths than grasslands or croplands. To preserve SOC stocks and reduce emissions, forest management techniques like reduced-impact logging and maintaining the integrity of the forest floor are essential (Jandl *et al.*, 2007). On the other hand, land conversion, intensive tillage and clear-cutting significantly diminish soil carbon pools, which exacerbates climate change (Guo & Gifford, 2002).

Recent studies also examine how mycorrhizal fungi mediate carbon fluxes between plants and soil, which affects nutrient cycling and soil carbon stabilization (Smith & Read, 2008; Averill *et al.*, 2014). It is becoming more widely acknowledged that comprehending carbon persistence and turnover in forest ecosystems requires an understanding of the intricate relationships among soil microbes, root exudates and soil minerals (Lehmann *et al.*, 2020).

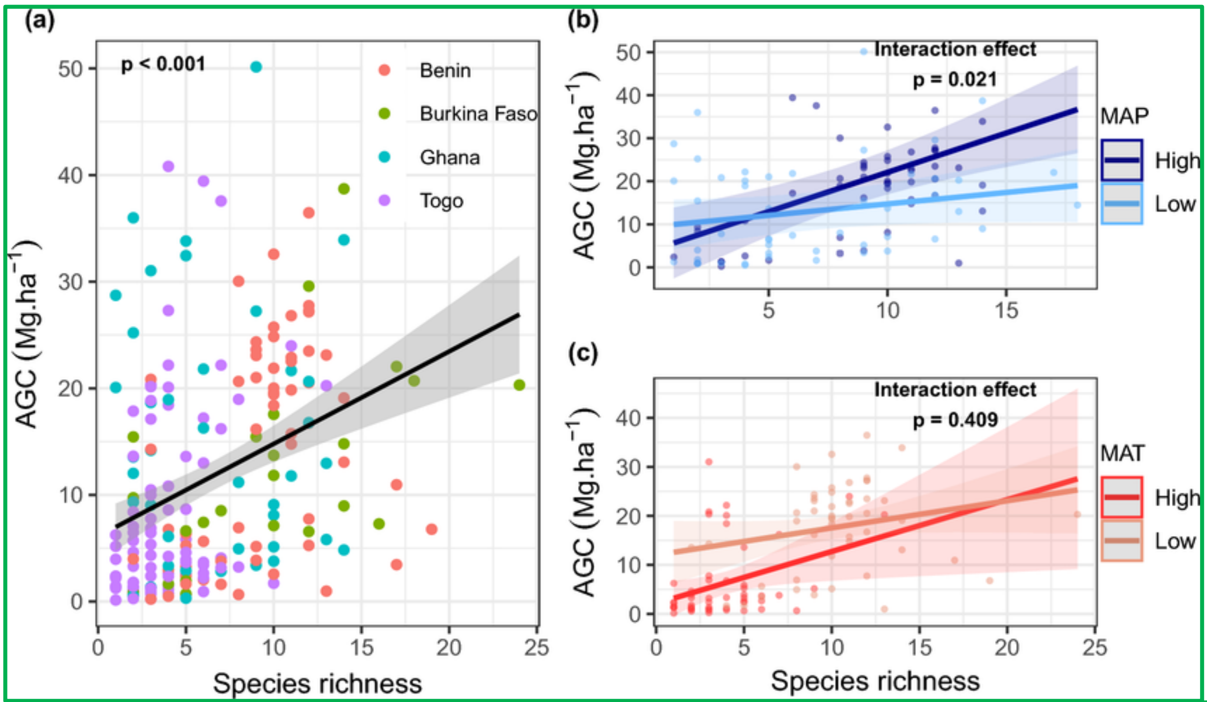
Biodiversity, Ecosystem Function and Carbon Stability

Carbon sequestration, resilience and productivity are among the ecosystem functions that biodiversity supports. Due to niche differentiation, complementary resource use and species-to-species interactions, ecological theory and empirical data show that species-rich forests are more stable and productive than monocultures (Tilman *et al.*, 1997; Loreau *et al.*, 2001). In a seminal study that examined more than 770,000 forest plots globally, Liang *et al.* (2016) discovered a strong positive correlation between aboveground biomass carbon stocks and tree species richness, highlighting the role of biodiversity in sequestering carbon.

In terms of resilience and productivity, mixed-species plantations typically perform better than monocultures (Paquette and Messier, 2011). During times of environmental stress, diverse forests maintain carbon uptake because they are more resilient to pests, diseases and climate extremes (Xu *et al.*, 2020; Isbell *et al.*, 2015). According to Diaz and Cabido (2001), functional diversity *or* the variety of ecological roles that species play, improves ecosystem services like carbon regulation and forest stability.

The interdependence of biodiversity and ecosystem services, such as carbon regulation, water cycling and nutrient retention, was highlighted in the Millennium Ecosystem Assessment (2005). The loss of biodiversity jeopardizes forest carbon storage and makes forests more vulnerable to climate shocks, according to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019), which also identified forest biodiversity as the cornerstone of climate resilience. Given the continuous global deforestation and fragmentation that lower species richness and interfere with ecosystem functions, this is especially pertinent (Newbold *et al.*, 2015).

Therefore, biodiversity conservation becomes essential for both climate adaptation and mitigation. Enhancing ecosystem health and strengthening carbon sequestration potential are two benefits of incorporating biodiversity-friendly forest management techniques, such as maintaining keystone species and encouraging structural complexity (Gamfeldt *et al.*, 2013).



Relationships between species richness and aboveground carbon (AGC) across (a) all plots; (b) under lower and higher mean annual precipitation (MAP); and (c) under lower and higher mean annual temperature (MAT). Lower and higher MAP (resp. MAT) were determined using the 25th and the 75th percentile scores respectively, for the MAP (resp. MAT) data across the plots (see "Material and methods" section). The lines represent the fitted values and shaded regions the pointwise 95% confidence interval around the fitted values. See Supplementary Table S2 online for additional statistics on the interaction effects.

Fig.3: Relationship between species richness and aboveground carbon storage (Liang *et al.*, 2016).

Forest Degradation, Deforestation and Carbon Emissions

Because of deforestation, degradation and disturbance, forests are becoming more and more sources of CO_2 emissions despite their potential to act as carbon sinks. According to estimates from the Food and Agriculture Organization (FAO, 2022), between 10 and 15 percent of anthropogenic greenhouse gas emissions each year are caused by land-use change, which is mostly caused by forest loss. With an estimated 1.5 petagrams of carbon released annually through biomass combustion, decay and soil carbon loss, tropical deforestation is the biggest contributor (Houghton & Nassikas, 2017).

Forest clearance is fueled by mining, logging, infrastructure development and commercial agriculture expansion, which frequently occurs in tropical biodiversity hotspots and exacerbates emissions and ecological degradation (Achard *et al.*, 2014). Although often underreported, forest degradation-which includes selective logging, understory removal and fire suppression-contributes significantly to carbon emissions (Baccini *et al.*, 2017). Degradation of this kind lowers forest carbon stocks, weakens forest resilience and makes the forest more vulnerable to future disturbances (Asner *et al.*, 2009). Due to poor governance and illicit activity, remote sensing technologies that use satellite imagery (e.g., MODIS, Landsat) have shown significant forest loss in places like Brazil and Indonesia, frequently even within legally protected areas (Margono *et al.*, 2014; Silva *et al.*, 2020). Deforestation spikes brought on by recent enforcement lapses and policy rollbacks have undone previous gains in climate mitigation and put global carbon budgets in jeopardy (Nepstad *et al.*, 2014).

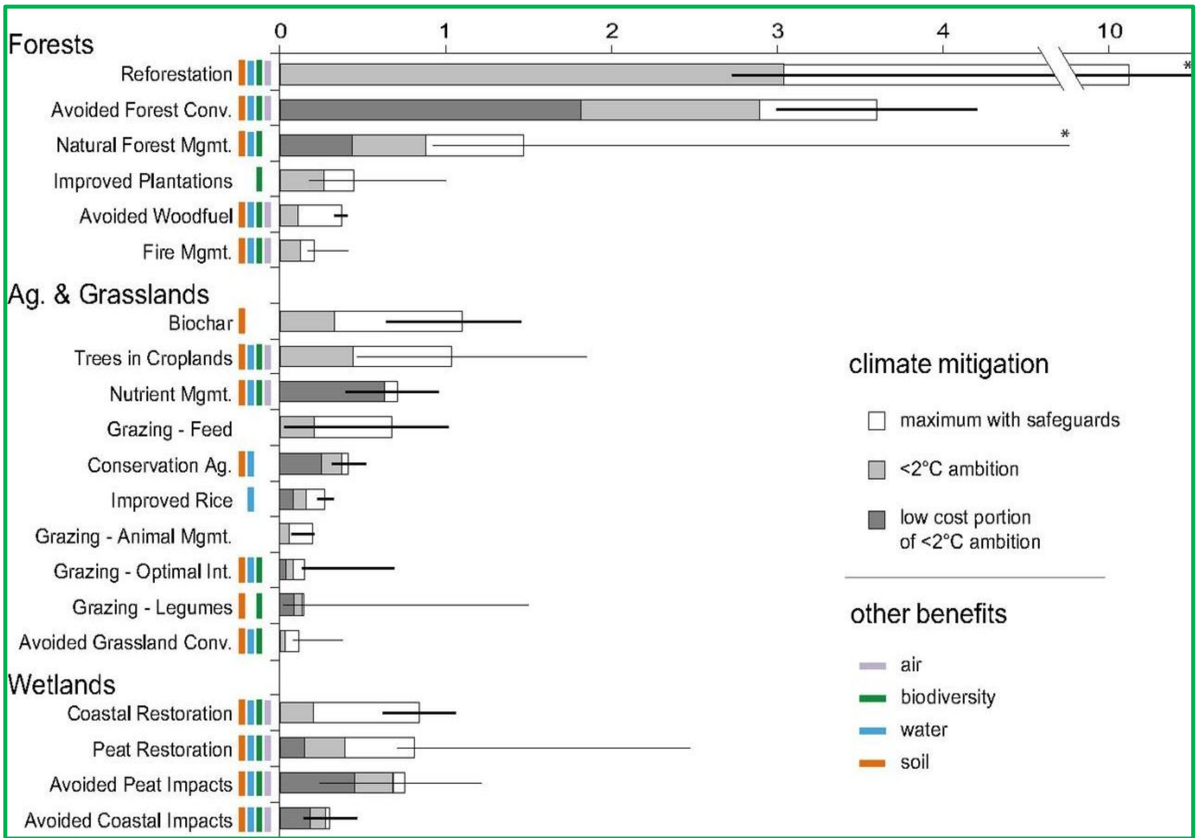
Forest fragmentation causes biodiversity loss, carbon stock declines and microclimatic changes by decreasing connectivity and increasing edge effects (Haddad *et al.*, 2015). It may take decades or even centuries for regrowth to pay off the carbon debt caused by deforestation, highlighting the critical need for conservation and sustainable management to stop additional emissions (Poorter *et al.*, 2016).

Reforestation, Agroforestry and Nature-Based Climate Solutions

Among the most promising nature-based climate solutions (NCS) for restoring carbon sinks and offering socio-ecological advantages are reforestation and agroforestry. Reforestation is the biggest natural climate mitigation opportunity (FAO, 2020) and Griscom *et al.* (2017) estimate that over 100 gigatons of CO_2 could be sequestered globally over the next three decades by restoring degraded forests and increasing tree cover. Paul *et al.* (2002) and Guo & Gifford (2002) have shown that reforestation of degraded or marginal lands enhances soil health, biodiversity and carbon stocks.

Through the integration of trees with crops and livestock, agroforestry systems improve farm productivity and resilience to climate variability while enhancing above- and belowground carbon storage (Nair *et al.*, 2010; Jose, 2009). In order to meet the objectives of climate mitigation and adaptation, India's National Agroforestry Policy (2014) encourages the use of tree-based farming systems to boost biomass, improve carbon sequestration and generate income (Chaudhary *et al.*, 2020). Crop yields, carbon storage and soil fertility have all improved in agroforestry in arid African regions using species like Faidherbia albida (Bayala *et al.*, 2015).

The multifunctional land use necessary for sustainable development is embodied by such integrated systems, which not only sequester carbon but also promote food security, water retention and biodiversity conservation (CIFOR, 2017). But policy support, capacity building and financial incentives like carbon markets and payment for ecosystem services (PES) are necessary for scaling up (Griscom *et al.*, 2020).



Climate mitigation potential of 20 natural pathways. We estimate maximum climate mitigation potential with safeguards for reference year 2030. Light gray portions of bars represent cost−effective mitigation levels assuming a global ambition to hold warming to <2 °C (<100 USD $MgCO_2e^{-1}\ y^{-1}$). Dark gray portions of bars indicate low cost (<10 USD $MgCO_2e^{-1}\ y^{-1}$) portions of <2 °C levels. Wider error bars indicate empirical estimates of 95% confidence intervals, while narrower error bars indicate estimates derived from expert elicitation. Ecosystem service benefits linked with each pathway are indicated by colored bars for biodiversity, water (filtration and flood control), soil (enrichment), and air (filtration). Asterisks indicate truncated error bars. See SI Appendix, Tables S1, S2, S4, and S5 for detailed findings and sources.

Fig.4: Estimated carbon mitigation potential of natural climate solutions (Griscom *et al.*, 2017)

Urban Forestry and Emerging Green Infrastructure Solutions

Urban forestry and green infrastructure present opportunities as well as challenges for global carbon management. By lowering city temperatures and sequestering significant carbon stocks, urban trees reduce the need for energy for cooling and the emissions that go along with it (Nowak *et al.*, 2013; McDonald *et al.*, 2016). According to Tzoulas *et al.* (2007), urban green spaces improve biodiversity, air quality, stormwater management and human well-being. Urban forests are promoted as important tools for climate adaptation and mitigation by India's Smart Cities Mission, which incorporates biodiversity enhancement and urban greening into city planning (MoHUA, 2021). Cities around the world, including Singapore and New York, have put in place urban forestry initiatives that show notable advantages in cooling and carbon sequestration (Gillner *et al.*, 2015). Green infrastructure is an essential part of sustainable, climate-resilient cities because it provides multi-sectoral benefits (Keesstra *et al.*, 2018).

Conclusion

Forests are dynamic, multipurpose ecosystems that support biodiversity, provide ecosystem services and sequester carbon in biomass and soils, all of which help to create a stable climate. There is unquestionable scientific agreement that managing, restoring and protecting forests is essential to reducing the effects of climate change. Forests' ability to absorb and store carbon is influenced by a variety of factors, including species composition, age of the forest, soil processes, biodiversity and human governance. Reducing deforestation and degradation, which turn carbon sinks into sources and hasten global warming, is equally critical. New studies emphasize how crucial it is to incorporate agroforestry, urban greening, sustainable forest management and biodiversity conservation as complementary approaches within more comprehensive climate policies. Harnessing the full climate potential of forests will require improving community involvement, strengthening governance and using market and policy mechanisms to incentivize nature-based solutions. How humans treat and preserve forests-not just as carbon sinks but also as vital pillars of the planet's ecological and social structure-will determine how stable the climate is in the future.

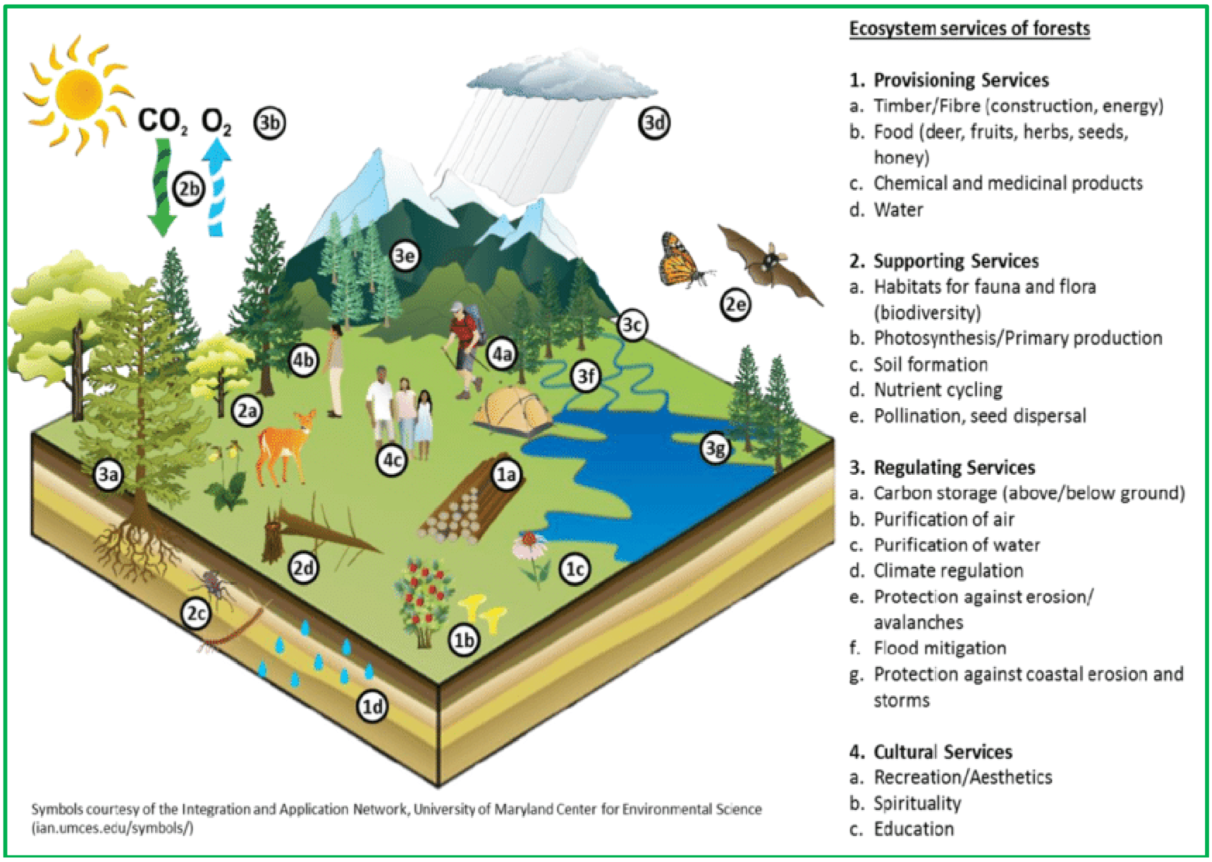


Fig.5: Multiple ecosystem services provided by forests (UNEP, 2022).

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