Tracking global reforestation progress and patterns under sustainability agendas

Zhenrong Du,[1] Le Yu,[2,3,4,*] Xinyue Li,[1] Lidong Mo,[5] Cong Ou,[6] Xiaorui Ma,[1] Jianqiao Zhao,[7] Pengyu Hao,[8] Hongyu Wang,[1] and Yongguang Zhang[9]

[1]School of Information and Communication Engineering, Dalian University of Technology, Dalian 116024, China
[2]Department of Earth System Science, Ministry of Education Key Laboratory for Earth System Modeling, Institute for Global Change Studies, Tsinghua University, Beijing 100084, China
[3]Ministry of Education Ecological Field Station for East Asian Migratory Birds, Department of Earth System Science, Tsinghua University, Beijing 100084, China
[4]Institute of Carbon Neutrality, Tsinghua University, Beijing 100084, China
[5]Department of Plant Biology and Ecology, College of Life Sciences, Nankai University, Tianjin 300071, China
[6]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[7]College of Land Science and Technology, China Agricultural University, Beijing 100083, China
[8]Food and Agriculture Organization of the United Nations, Viale delle Terme di Caracalla, Rome 00153, Italy
[9]International Institute for Earth System Sciences, Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing University, Nanjing 210023, China
*Correspondence: leyu@tsinghua.edu.cn

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Dear Editor,

Reforestation has emerged as one of the key solutions for climate change mitigation and ecosystem restoration.[1] Planted forests are recognized for their ability to deliver both wood products and ecosystem services, including carbon sequestration, biodiversity enhancement, and erosion control.[2] Over the past three decades, governments and non-government organizations around the world have launched various ambitious restoration initiatives to combat land degradation, ecosystem restoration and accomplish sustainability goals in the fight against climate change.[3] However, the spatial and temporal progression of these efforts at a global scale still remains insufficiently investigated and poorly understood. To date, existing statistics, such as those compiled by the Food and Agriculture Organization (FAO),[4] provide national-level estimates of planted forest area and associated carbon gains, but lack the spatial granularity and temporal consistency needed to accurately assess ecological outcomes or evaluate policy effectiveness.

Effective top-down monitoring of global forest gain requires both long-term Earth observation data and accurate delineation of planted forest boundaries. Yet, the fragmented distribution of planted forests across the globe, the variations in land management intensity, and the diversity of restoration strategies–ranging from commercial plantations to ecological restoration efforts–pose significant challenges for consistent global monitoring. Here, we present a high-resolution (30 m) global annual plantation forest gain dataset from 1990 to 2024, developed by integrating Landsat satellite observations with a global planted forest mask derived from the Spatial Database of Planted Trees (SDPT v2.0).[5] Furthermore, to identify the initial planting year for each pixel, we applied the spectral trajectory segmentation approach of LandTrendr. In addition, we integrated the initial planting year with climate and topographic data to explore spatiotemporal shifts in reforestation patterns and environmental contexts. Finally, we assessed ecological recovery dynamics by tracking changes in vegetation density, canopy structure, and ecosystem productivity using three widely adopted remote sensing indicators: normalized difference vegetation index (NDVI), leaf area index (LAI), and gross primary productivity (GPP). To evaluate how recovery trajectories of planted forests have transited under shifting global restoration priorities, we compared vegetation recovery patterns before and after the adoption of the Sustainable Development Goals (SDGs) in 2015. In addition, we compared the recovery trajectories of planted forest sites with those of neighboring naturally regenerated forests to assess the relative contributions of active versus passive restoration strategies. Together, these analyses offer new insights into the global progression of planted forests—not only from a spatiotemporal perspective, but also in terms of ecological effects—providing the first spatially explicit and temporally resolved benchmark for evaluating plantation forest impacts over the past three decades.

The developed high-resolution (30 m) global forest planting year dataset, spanning 1990–2024, reached an F1-Score of 86.46% with a tolerance of ±5 years. This map reveals heterogeneous spatial and temporal patterns in tree planting efforts worldwide (Figure 1A). Regions with intensive forest planting activity included China, southeastern Brazil, the southeastern United States, and parts of Europe and Southeast Asia. Notably, planting years of these plantations in China, the United States, and much of Europe are predominantly concentrated between 1990 and 2005. In China, these temporal and spatial patterns closely align with the implementation of major national ecological restoration projects, including the "Grain for Green" Program and the Three-North Shelterbelt Project. In the United States and Europe, forest planting surges during this period are likewise associated with the Conservation Reserve Program and the European Union's Common Agricultural Policy, respectively. Meanwhile, South America, particularly southeastern Brazil, exhibited a peak in forest planting activity around 2010, which follows the launch of the Atlantic Forest Restoration Pact in 2009.[6] Since 2015, forest planting efforts have become increasingly concentrated in tropical regions around equator, with notable activity in countries such as Indonesia, the Philippines, and Viet Nam. These recent hotspots reflect an expanding geographical focus of global restoration efforts and the deepening integration of reforestation into climate mitigation and biodiversity agendas.

Temporal analysis showed a notable increase in plantation area from the early 1990s till the late 2000s, followed by a decline in the last decade, consistent with FAO-reported statistics (Figure 1C).[4] To further characterize the shifting environmental context of these plantations, we assessed temporal trends in mean annual precipitation, elevation, and slope across all forest plantation pixels (Figure 1D). Results indicate a gradual shift of reforestation activities from drier and steeper regions in the 1990s toward more humid, lowland areas in recent years. Specifically, annual precipitation of these areas increased from ~1,100 mm to over 1,400 mm, while average elevation and slope declined by ~50 m and ~2°, respectively. This trend suggests a transition from early large-scale forest planting projects in marginal lands, such as degraded slopes or semi-arid zones, toward ecologically favorable regions with greater restoration potential and higher carbon sequestration ability. Reforestation now increasingly targets tropical and sub-tropical zones where higher baseline productivity, longer growing seasons, and stronger hydrological coupling enable more rapid canopy closure, accelerated carbon uptake, and enhanced biodiversity co-benefits.

Despite this overarching shift, regional divergences were observed when reforestation year modes were aggregated at the ecoregion scale (Figure 1B). Notably, several dryland regions, including the Sahel and the Central Asian steppe, exhibited recent increases in reforestation activities, diverging from the global trend toward wetter zones. These hotspots of late-stage reforestation reflect targeted restoration initiatives in climate-vulnerable ecosystems, such as the African Great Green Wall,[7] which aims to combat desertification and enhance ecosystem resilience. Together, these findings highlight both the spatial realignment and regional persistence of reforestation efforts under diverse environmental and policy contexts.

To identify high-density regions of tree planting before and after the launch of the Sustainable Development Goals (SDGs) in 2015, we examined the

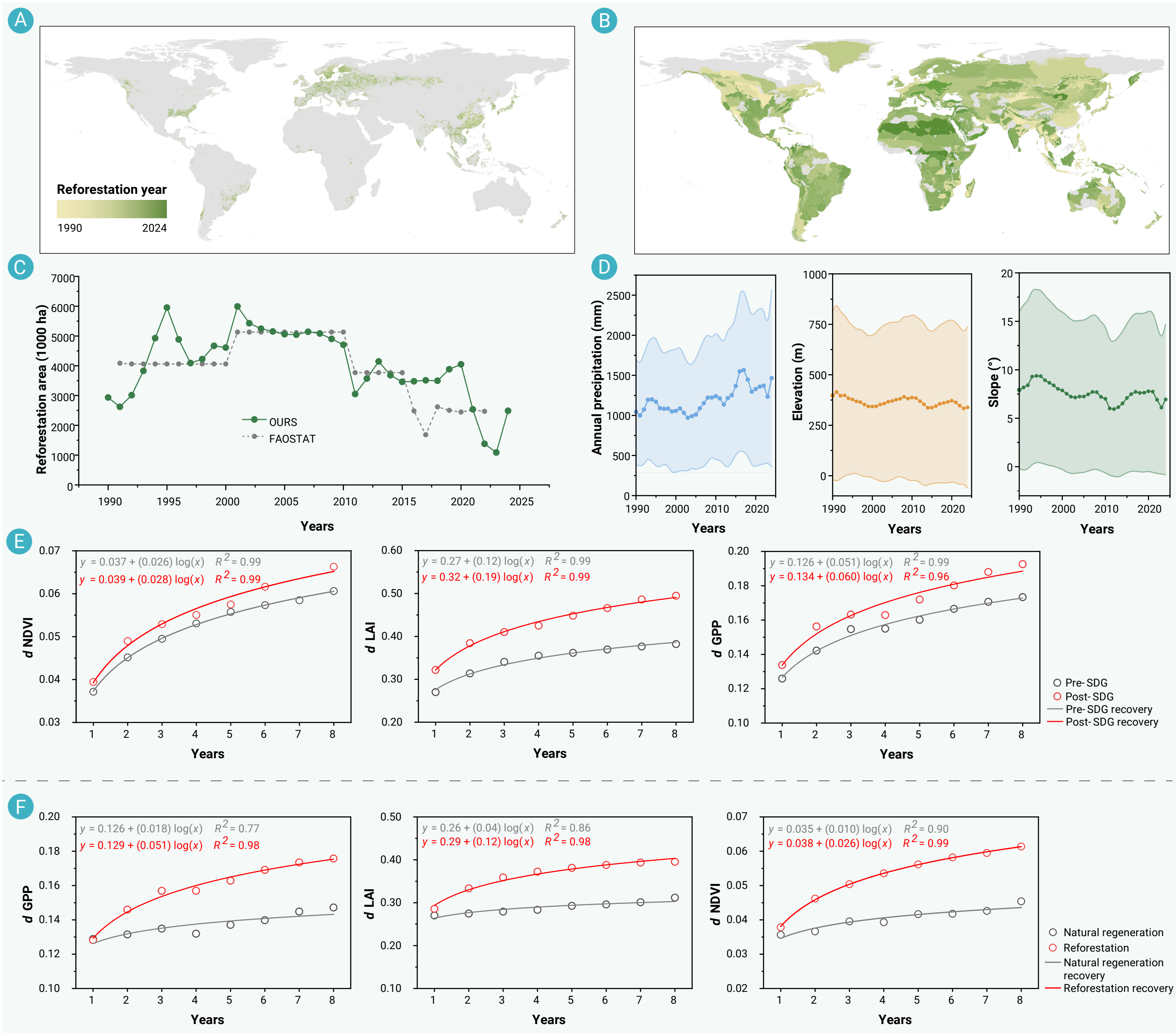

Figure 1. Global spatiotemporal patterns, environmental gradients of reforestation from 1990 to 2024, and vegetation recovery trajectories (A) Annual reforestation year map (30 m resolution) based on Landsat time series and LandTrendr segmentation (1990 – 2024). (B) Mode reforestation year (i.e., most frequent year of reforestation) overlaid on global terrestrial ecoregions. (C) Compare global annual reforestation area derived from this study (OURS) with FAOSTAT planted forest statistics. (D) Temporal trends of mean annual precipitation (left), elevation (middle), and slope (right) for all reforested pixels. Shaded areas indicate one standard deviation. (E) Vegetation structural and functional recovery trends for reforestation areas prior to the adoption of the SDGs ("Pre-SDG") and the SDG agenda ("Post-SDG"). (F) Recovery trends in natural regeneration areas and reforested areas. Open circles represent annual means, with solid lines denote best-fit nonlinear regressions (log-transformed), with corresponding equations and coefficients of determination (R^2) shown. The slope coefficient of the logarithmic term reflects the vegetation recovery rate, where higher values indicate faster structural and functional recovery following reforestation.

spatial clustering of reforestation hotspots using Local Moran's I statistic,[8] and important shifts are evident. Before 2015, reforestation efforts were strongly concentrated in northern temperate regions, including northeastern China, eastern Europe, and the midwestern United States, often associated with national-scale land restoration programs such as China's Grain-for-Green initiative and the U.S. Conservation Reserve Program. In contrast, the post-SDG period reveals a more spatially diffuse and equatorward shift, with increased hotspot density observed in tropical Asia, South America, and parts of Sub-Saharan Africa, reflecting growing attention to restoration in biodiversity-rich and climate-vulnerable ecosystems under the SDG framework. The emergence of new high-high clusters in equatorial regions also highlights the spatial expansion of reforestation priorities toward degraded tropical landscapes.

To evaluate the recovery of ecosystem functions in planted forests, we quantified the temporal trajectories of three vegetation recovery metrics—Normalized Difference Vegetation Index (NDVI), Leaf Area Index (LAI), and Gross Primary Productivity (GPP)—as a function of plantation age using a log-transformed model (Figure 1E). Across all vegetation metrics, forest planting led to improved vegetation structure and increased productivity within the first eight years. Notably, the fitted slope parameters (b) for NDVI (0.026 vs. 0.028), LAI (0.12 vs. 0.19), and GPP (0.051 vs. 0.060) were all higher in the post-SDG period compared to the pre-SDG period, suggesting a modest acceleration in vegetation recovery rates in recent reforestation efforts. The stronger LAI and GPP responses in particular imply more effective ecosystem functioning and biomass accumulation in post-SDG reforestation zones. This enhancement is likely associated with the geographical shift of reforestation activities toward tropical and humid regions over the past decade, where higher temperature and precipitation regimes promote faster canopy development. It is also likely influenced by concurrent improvements in restoration practice, such as the use of fast-growing and climate-adapted genotypes, mixed-species planting, and post-planting management. These findings indicate that, while the spatial focus of reforestation has shifted from temperate to tropical regions under the SDG agenda, the ecological efficiency of restoration has also improved. This underscores the dual progress in reforestation extent and effectiveness in the post-SDG global restoration landscape.

Further comparative analysis between reforestation and natural regeneration (Figure 1F) reveals that reforested areas exhibit higher rates of vegetation recovery during the first eight years after forest planting. Specifically, the NDVI recovery rate (b = 0.026) for reforested areas was more than double that of natural regeneration (b = 0.010), while LAI recovery (b = 0.12 vs. 0.04) and GPP recovery (b = 0.051 vs. 0.018) showed similarly differences. These results suggest that planted forests achieve higher rates of vegetation recovery than naturally regenerated forests, particularly in terms of canopy development and photosynthetic productivity. However, this difference should not be interpreted as a universally superior ecological outcome of planted forests. Natural regeneration typically occurs following disturbances such as wildfire, drought, or logging, where canopy cover, soil structure, and seed banks have already been degraded, resulting in slower early recovery. In contrast, reforestation usually involves deliberate seedling establishment, species selection, and site preparation, which reduces ecological bottlenecks that constrain spontaneous succession. The advantage of planted forests is also influenced by the recent shift of large-scale planting efforts toward tropical and humid regions, where warm and wet conditions, long growing seasons, and rapid nutrient cycling inherently accelerate biomass accumulation.

Our results highlight a dual transition in global reforestation patterns over the past three decades. Spatially, reforestation efforts have shifted from temperate zones toward tropical regions, while temporally, we observe a decline in global reforestation extent after a peak during 2000—2010. Concurrently, the recent shift of reforestation toward tropical and humid regions has enhanced ecological performance, with post-SDG reforestation exhibiting accelerated recovery of vegetation structure and productivity during the first eight years. These findings underscore not only the evolving spatial focus of restoration, but also the increasing ecological efficiency of targeted reforestation strategies in the SDG era.

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AUTHOR CONTRIBUTIONS

L.Y. conceived the idea, Z.D. and L.Y. conducted the experiment, all authors provided recourses and analyzed the results. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.