Greener but not taller: LiDAR shows South Asia's forest greening is concentrated in structurally depleted forest

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Greener but not taller: LiDAR shows South Asia's forest greening is concentrated in structurally depleted forest

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Abstract

India and China lead the world in greening, and forest greening is widely read as a sign of recovery. Greenness, however, tracks foliage and says little about forest type or height. MODIS greening trends for 2001 to 2024 and a new 10 m map separating natural forest from plantations and tree crops showed that natural forest supplied 65% of South Asia's woody greening. Against least-disturbed forest of the same ecoregion and elevation, GEDI LiDAR showed strongly depleted forest to be 17 percentage points more likely to green than reference-like forest, and over half the greening natural forest was depleted. An independent Landsat record tied depleted forest to past disturbance and its greening to regrowth. Natural forest lacks 592 Tg (15%) of reference aboveground carbon, 60% of the deficit in greening forest. Forest greening in South Asia largely marks regrowth in forest that remains structurally depleted, not forest that has recovered.

Keywords

forest greening; forest degradation; forest recovery; GEDI; spaceborne LiDAR; canopy height; reference condition; carbon deficit; restoration; South Asia

PLAIN-LANGUAGE SUMMARY

India and its neighbors are among the fastest-greening places on Earth, and governments, funders and the public often take a greener forest to be a healthier one. Satellite greenness records track leaves, however, and say little about how tall a forest is or how much wood it holds. We combined two decades of satellite greenness records with a new map that separates natural forests from plantations and with laser measurements of forest height from space. Most greening was in natural forests, and it

was most common in those shorter than the best remaining forests of their kind, usually forests disturbed in the past and now regrowing. The region's natural forests lack about 592 million tonnes of carbon compared with least-disturbed forest, and 60% of that deficit lies in forests that are greening. In India, the carbon missing from natural forest is nearly three times what new forests and trees on farms could add. Restoration pledges and climate targets that count greener or more tree-covered land as recovered forest may therefore overstate progress. Adding LiDAR height to national forest monitoring, and protecting regrowing forests long enough for them to grow tall again, would make these targets more credible.

Introduction

Satellite records show that much of the Earth's vegetated land has greened since the early 1980s,[1] and that India and China lead this greening.[2] Among the world's largest countries, India has the highest share of vegetated land that is greening,[2] and greener land is increasingly read as a sign of environmental success. This reading is built into global reporting. The land-productivity sub-indicator of SDG 15.3.1, the Sustainable Development Goal indicator of land degradation, uses NDVI as a proxy for productivity, and a widely used tool for computing it treats a significant positive NDVI trend as potential improvement in land condition, although the indicator's guidance cautions that rising productivity can also signal shrub encroachment.[3,4] Forest and tree cover also carry much of South Asia's climate and restoration commitments. India has pledged to restore 26 million hectares of degraded land under the Bonn Challenge[5] and to create an additional carbon sink of 2.5 to 3 billion tonnes of CO_2 equivalent through additional forest and tree cover by 2030.[6] In Pakistan, rising NDVI at Billion Tree Tsunami planting sites has been reported as evidence of "vegetation recovery and reversing chronic ecosystem degradation".[7]

Greenness, however, tracks foliage rather than forest structure. Vegetation indices such as NDVI and EVI respond to the amount and condition of foliage in the canopy[8,9] and say little about the height of trees, the size of stems or the biomass they hold. These attributes recover at very different rates. In secondary forest regrowing on abandoned pasture in central Amazonia, canopy cover was close to old-growth values after 12 to 14 years, whereas biomass remained at a quarter to a half of them.[10] Across tropical chronosequences, forest structure takes several decades and aboveground biomass more than a century to approach old-growth values.[11] Structure also stores the carbon, provides habitat for canopy-dependent species and buffers the forest interior against heat. Closed canopies keep maximum temperatures below those of open land,[12] and where canopies open, understory plant communities shift faster toward warm-adapted species.[13] Greening can also arise without any gain in structure, through denser or compositionally different vegetation,[1] encroachment of woody plants into open land,[14,15] or a simpler canopy that casts fewer shadows and so raises EVI.[16] At sites where drought and heat had killed large numbers of trees, decadal greening still dominated the satellite record,[17] so greening can even hide structural loss.

This ambiguity is acute in South Asia's forests. Much of the region's natural forest is tropical moist and dry deciduous forest, dominated by sal (*Shorea robusta*) and teak (*Tectona grandis*), together with subtropical pine and temperate broadleaf forest in the Himalaya and evergreen

forest under shifting cultivation in the northeast. People depend on these forests for fuelwood, fodder and timber, and the pressures this creates are chronic rather than catastrophic. Fuelwood collection, lopping for fodder, grazing and fire remove large trees and suppress regeneration while the canopy persists,[18,19] shifting cultivation leaves mosaics of fallow forest at different stages of regrowth,[20] and the invasive shrub *Lantana camara* occupies an estimated 39% of surveyed Indian forest.[21] The statistics used to track these forests measure cover and say little about condition. In India, forest cover rose while the growing stock of wood fell,[22] reported gains have come largely from plantations[23,24] and are not readily visible in Landsat time series,[25] and the undisturbed moist tropical forest of 1990 had shrunk by 56% by 2019.[26] In India's dry woodlands, a net gain over the past decade has masked the loss of native woodland on government forest land.[27] Tree planting in the Himalaya has not raised canopy cover,[28] and in central India the densest canopy class expanded while signs of forest use persisted beneath it.[29]

The most widely cited account of India’s greening did not examine whether forests could green while remaining structurally depleted. Chen et al.[2] attributed India's greening to land-use management, mainly the intensification of cropping, and judged the contribution of forests to be minor because forests added only 4.4% of the country's net increase in leaf area. They also described greening lands as becoming more productive. By the same analysis, however, Indian forests greened over 47% of their area between 2000 and 2017, so greening forest is not minor in extent. More fundamentally, leaf area cannot distinguish a forest that has kept its structure from one that is regrowing on a depleted structure, or from one in which shrubs and lopped regrowth have replaced large trees. Global land-cover maps also class plantations and many tree crops as forest, so they cannot say whether greening forest is natural or planted.[30] The attribution of India's greening to human management therefore leaves open what kind of forest is greening, and answering that question requires a map of forest types and a measure of forest structure that is independent of greenness.

Optical and LiDAR studies have each approached the question without answering it. In Southeast Asia, matched comparisons with stable forest show that regional greening between 2001 and 2022 masked the greenness and productivity forgone where forest was lost,[31] although stable forest in such comparisons can itself be degraded, and optical indices cannot show how much structure the remaining forest has lost. In a central Indian national park whose vegetation greened between 2001 and 2016, about a third of the area was classified as degraded forest,[32] but this evidence comes from classifying reflectance at a few sites, without

testing whether the degraded patches are the ones that green. Spaceborne LiDAR now measures structure directly. Since 2019, the Global Ecosystem Dynamics Investigation (GEDI) has sampled canopy height across the tropics and subtropics,[33] revealing that degraded tropical moist forest is at least 10 m lower than intact forest and that regrowing forest plateaus at about 60% of intact height.[34] Globally, a GEDI-based index of forest structural density is lower where human pressure is higher, and human pressure is its dominant correlate across much of India.[35]

In an earlier study, we found that greening in the Hindu Kush Himalaya spans forests of very different height and biomass,[36] but that study used absolute height thresholds, which do not transfer across South Asia. A 15 m canopy is mature in dry deciduous forest and depleted in montane broadleaf forest. The appropriate benchmark is the best remaining forest of the same kind, an approach long used to assess ecological condition against least-disturbed reference sites.[37] No study has yet tested, at the scale of a subcontinent, whether greening is concentrated in forest that is structurally depleted relative to such a benchmark, or whether that depletion reflects past disturbance.

Here we test two explanations of forest greening in South Asia. If greening reflects a general increase in forest growth, from rising CO_2, nitrogen deposition or a changing climate,[1,38] it should be about as common in depleted forest as in forest whose structure matches least-disturbed forest of the same ecoregion and elevation, and unrelated to disturbance history. If instead greening reflects regrowth after disturbance, greening should be concentrated in depleted forest, depleted forest should carry a longer history of disturbance, and greening depleted forest should be regrowing after earlier disturbance. Whether regrowing forest will regain the structure of least-disturbed forest is a separate question that requires repeated measurements of height. We first ask what vegetation is greening, by combining MODIS greening trajectories for 2001 to 2024 with a new 10 m global forest typology that separates natural forest from plantations and tree crops,[30] across 912,687 km^2 of woody vegetation outside cropland mosaics. We then ask what structure is greening, by classing GEDI canopy height relative to least-disturbed reference forest of the same ecoregion and 500 m elevation band. Specifically, we ask: (i) is greening concentrated in structurally depleted forest; (ii) does an independent Landsat record of disturbance and regrowth support regrowth on depleted structure; and (iii) how much aboveground carbon does natural forest lack relative to reference forest, and how much of that deficit lies in greening forest?

Results

We classified each 1 km cell at two levels (Figure 1): by vegetation type and greening trajectory, and, where forest covered at least 70% of the cell, by canopy height relative to reference forest of the same ecoregion and 500 m elevation band.

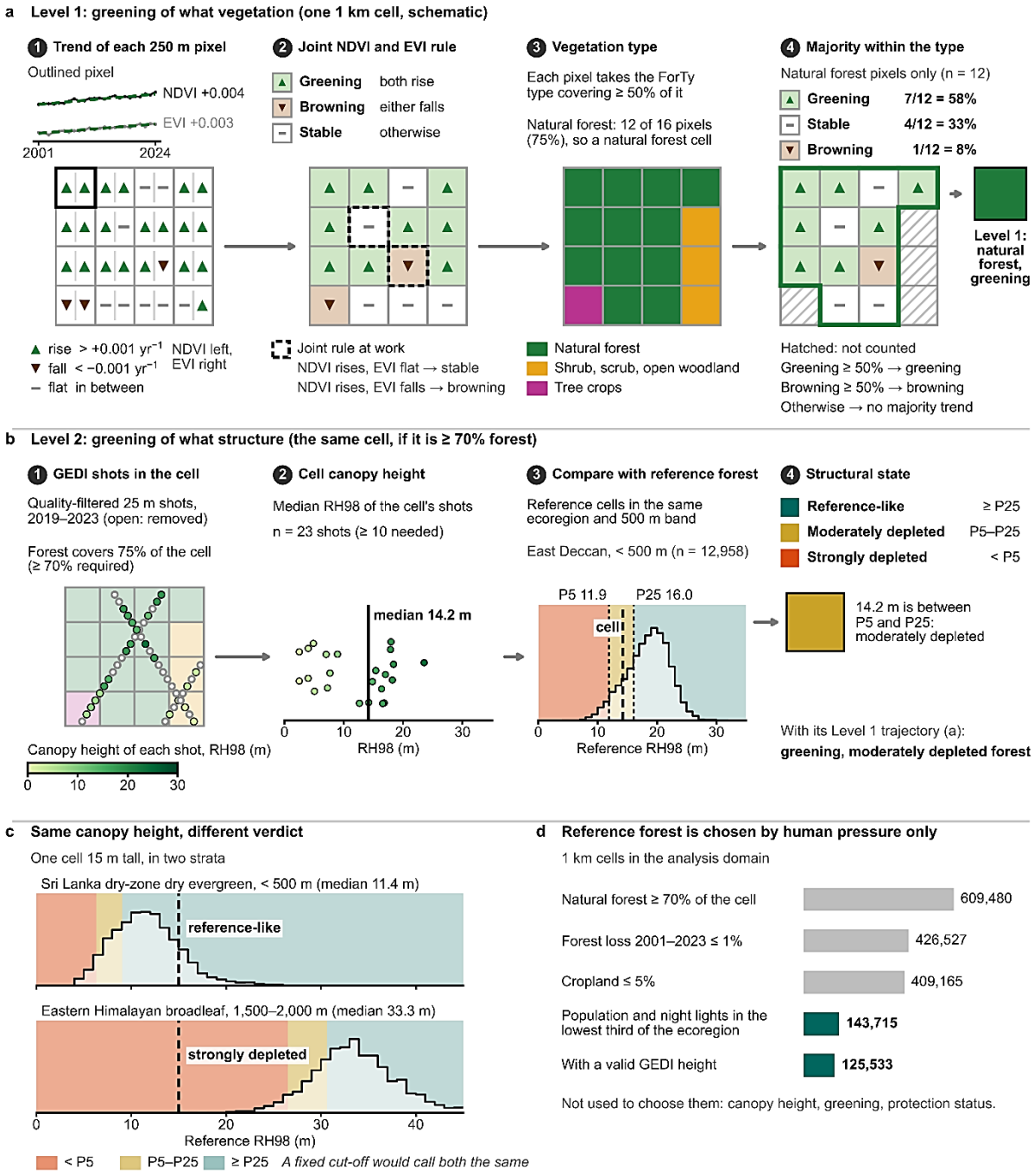


Figure 1. How each 1 km cell is classified by greening trajectory and structural state

(a) Level 1, for one schematic cell: Sen slopes of annual mean NDVI and EVI in each 250 m pixel, the joint rule, and the majority trajectory among pixels of the cell's vegetation type. (b) Level 2, for the same cell: GEDI shots are

schematic; the reference distribution is real (East Deccan moist deciduous forests, 0 to 500 m). (c) Real reference distributions of two strata. (d) Selection of reference cells; numbers are 1 km cells remaining after each criterion.

Greening of what vegetation

We found that half of South Asia's woody vegetation outside cropland mosaics greened between 2001 and 2024, and that most of this greening was natural forest (Figure 2). Under a rule that required both NDVI and EVI to increase (Figure 1a; Methods; datasets in Table S1), 51.3% of the 912,687 km^2 woody domain was greening and only 1.3% was browning. Natural forest supplied 64.9% of all greening, shrub, scrub and open woodland 29.9%, tree crops 4.9% and planted forest 0.3%, so one-third of the region's woody greening came from vegetation that is not forest. Within natural forest, 49% of the area was greening across South Asia (Figure 2g) and 52% in India. Over 2001 to 2019, a period closer to the years 2000 to 2017 in which Chen et al. found 47% of Indian forest greening by MODIS leaf area index with a different trend test,[2] the shares were 29% and 28%, so much of the forest greening detected over 2001 to 2024 appears only when the years after 2019 are included.

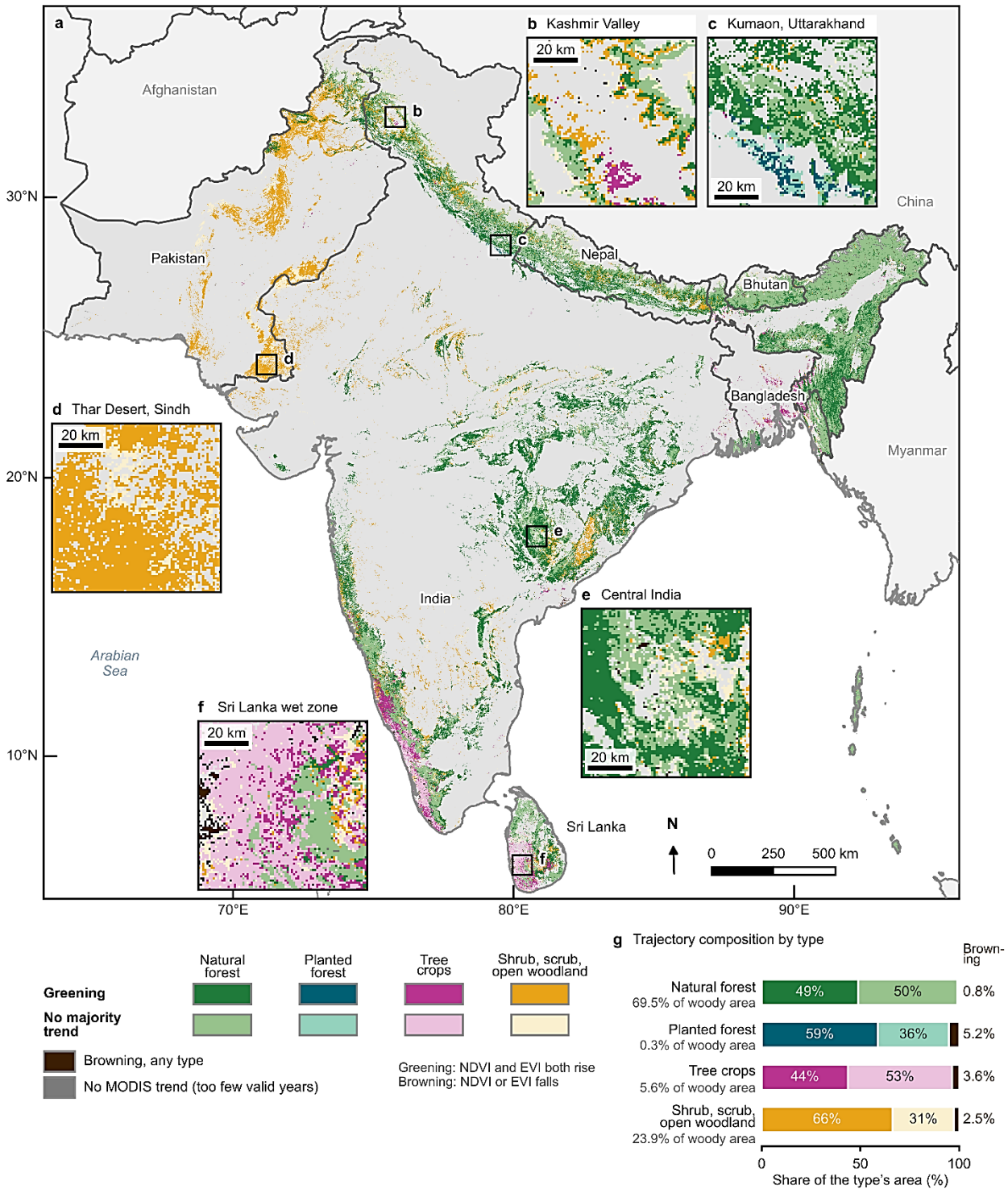


Figure 2. Half of South Asia's woody vegetation greened between 2001 and 2024, most of it natural forest: (a) Vegetation type (ForTy 2020) and majority MODIS NDVI and EVI trajectory of each 1 km cell of the woody domain, outside cropland mosaics. (b–f) 80 × 80 km windows. (g) Share of each type's area by trajectory. Boundaries as recognized by India; Albers equal-area projection. The map in (a) is the Level 1 map of the South Asia Greening Explorer, a Google Earth Engine app: https://ee-nbm.projects.earthengine.app/view/south-asia-greening-explorer.

The vegetation that greened, however, differed sharply between countries (Figures 2b–2f; Table 1; Table S2). In Pakistan, 85% of greening was shrub, scrub and open woodland. Rainfall over the Thar region, which extends into southeastern Pakistan, rose by 64% between 2001 and 2023,[39] and woody plants, including invasive mesquite (*Prosopis juliflora*), have spread into arid and semi-arid land in the region.[40] Greening of this vegetation is therefore likely to combine a response to rain with woody encroachment, neither of which is forest recovery. The irrigated farmland that dominates greening in the Thar[39] lies largely outside our domain. In Bangladesh and Sri Lanka, tree crops supplied 37% and 28% of greening. In India, Nepal and Bhutan, natural forest dominated, contributing 77% to 93% of greening. The share of woody vegetation that greened was lowest in the closed forests of Bhutan (17%) and highest in Pakistan (73%) and India (51%).

Table 1. Greening and structural state of woody vegetation by country

Unit	Woody domain (km²)	Greening (%)	From natural forest (%)	From shrub, scrub and open woodland (%)	From tree crops (%)	Assessed (%)	Ref.-like (%)	Mod. depleted (%)	Str. depleted (%)	Greening, ref.-like (%)	Greening, str. depl. (%)	Gap within strata, points (95% CI)	Strata
India	625,377	51.3	76.9	18.0	4.7	87.3	53.0	27.2	19.8	48.2	56.5	14.9 (11.4–17.7)	99
Pakistan	116,570	72.9	14.5	85.3	0.2	92.7	44.6	24.9	30.5	51.9	77.3	4.4 (0.1–10.9)	18
Nepal	73,964	45.5	81.0	18.3	0.1	91.5	46.6	31.1	22.3	34.3	62.4	24.3 (18.5–27.2)	27
Bhutan	31,830	17.4	92.7	7.3	0.0	94.9	64.1	21.8	14.1	8.2	38.5	23.6 (11.8–35.9)	15
Bangladesh	23,423	37.6	52.3	10.7	36.9	94.3	66.1	15.1	18.7	26.2	22.1	8.0 (−16.8 to 27.2)[a]	4
Sri Lanka	41,524	34.9	55.0	16.5	28.4	83.6	74.5	20.3	5.2	31.8	37.9	9.0 (−12.8 to 25.3)[a]	3
South Asia	912,687	51.3	64.9	29.9	4.9	88.2	53.9	26.7	19.5	43.1	56.1	16.6 (13.0–19.3)	116

Woody domain: 1 km cells with tree and shrub cover of at least 10% and cropland below 10%. Greening: share of the domain greening (NDVI and EVI both increasing, 2001 to 2024), pixel-weighted (Methods); the next three columns split each unit's greening by vegetation type (planted forest, 0.3% of greening, omitted). Assessed: share of forest with a structural state. Ref.-like, Mod. depleted, Str. depleted: percentages of assessed forest. Greening by state: natural forest, majority rule. Gap within strata: strongly depleted minus reference-like, averaged over ecoregion × elevation-band strata, with 95% confidence intervals from a spatial block bootstrap (Methods). Units are the areas each country administers. [a]Fewer than five strata; not interpreted.

Greening is concentrated in structurally depleted forest

Because natural forest supplied most of the region's woody greening, we next examined the structure of that forest, using canopy height, the height below which 98% of the GEDI LiDAR return lies (RH98). Canopy height captures the slow, structural part of forest recovery and reveals degradation that optical records miss,[34] and the LiDAR measures it directly, whereas biomass is modeled from it. Because forests differ in their natural stature, we expressed each 1 km cell's height relative to least-disturbed reference forest of the same ecoregion and 500 m elevation band, selected by low human pressure and without reference to structure or greenness (Methods; Figures 1b–1d). Cells at or above the 25th percentile of reference heights were classed as reference-like, cells between the 5th and 25th percentiles as moderately depleted, and cells below the 5th percentile as strongly depleted. These benchmarks differ widely between forest types (Table S3). The 25th percentile of reference height was 9.1 m in the dry evergreen forest of Sri Lanka's dry zone and 30.6 m in eastern Himalayan broadleaf forest between 1,500 and 2,000 m, so a 15 m canopy is reference-like in the first and strongly depleted in the second. In deciduous forest, most cloud-free GEDI shots are taken in the dry season, when trees are leafless. Leaf-off shots differed from leaf-on shots by only 0.1 m in median canopy height (Methods), and including them gave a structural state to 88.2% of the 557,751 km^2 of forest, against 62.6% with leaf-on shots alone.

Of the assessed forest, 53.9% was reference-like, 26.7% moderately depleted and 19.5% strongly depleted (Figure 3; Table 1; Table S4). Because the benchmarks are percentiles of reference forest, a quarter of reference forest itself falls below the 25th percentile and 5% below the 5th, so these classes describe structure relative to reference forest; their reading as depletion rests on how far they exceed those shares and on the disturbance record below. Depleted natural forest exceeded the share expected from reference variability by 21.1 percentage points (95% confidence interval 18.1–24.7), and strongly depleted forest was 3.9 times as common as expected (3.4–4.6). The excess changed little with the benchmark percentiles (20 to 21 points with benchmarks at the 2.5th and 15th, 5th and 25th, or 10th and 33rd percentiles), although the depleted share itself ranged from 35% to 54% (Table S5). Depleted forest made up about half of assessed forest in Nepal (53%), Pakistan (55%) and India (47%), but only 36% in Bhutan and 25% in Sri Lanka. Depleted forest formed continuous belts in the western Himalayan foothills, where most of it was strongly depleted (Kangra Valley, Figure 3b), in the Siwalik Hills of western Nepal (Figure 3d) and in the hills of northeast India, whereas most forest in Kumaon, about 400 km southeast of Kangra, was reference-like (Figure

3c). Much of the deciduous forest of central India, by contrast, was reference-like relative to its own, naturally lower benchmarks (Figure 3e). In Mizoram, depleted and reference-like cells formed a fine mosaic (Figure 3f), as expected where shifting cultivation leaves fallows of different ages, although individual cell states are uncertain in such steep terrain.

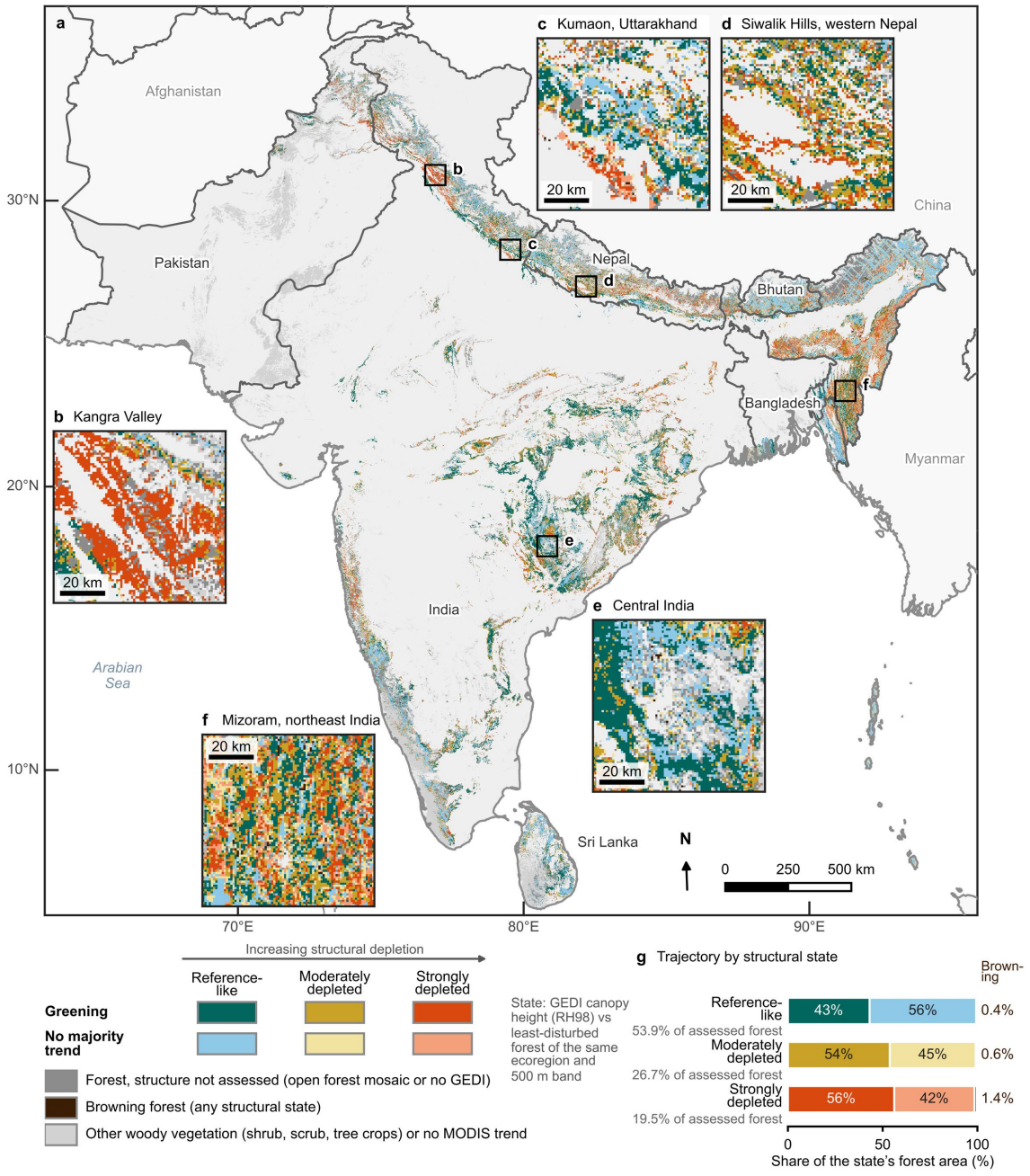


Figure 3. Strongly depleted forest is about four times as common in South Asia as reference variability alone would produce: (a) Structural state of forest (forest share ≥ 0.7) from GEDI canopy height (RH98, 2019 to 2023), classed as in Figure 1b, for greening forest and forest with no majority trend; by construction, 25% of reference forest

falls below the 25th percentile and 5% below the 5th. (b–f) 80 × 80 km windows. (g) Trajectory composition of each state (0.2% to 0.3% had no MODIS trend). The map in (a) is the Level 2 map of the same app.

Greening was concentrated in depleted forest, as the regrowth interpretation predicts (Figures 3g and 4a). It covered 43.1% of reference-like natural forest (95% confidence interval 37.6–48.4), 53.8% of moderately depleted forest (48.6–58.1) and 56.1% of strongly depleted forest (51.3–61.8). Because greenness and structure both vary with climate and elevation, the more informative comparison is within ecoregion and elevation band. There the difference between strongly depleted and reference-like forest was 16.6 percentage points (13.0–19.3), larger than the 13.0 points (7.8–19.0) over all forest, and it was positive in 87% of the 116 strata with enough cells of both states (Figure 4b; Table S6). As a result, 52% of greening natural forest was depleted, against 40% of natural forest with no majority trend.

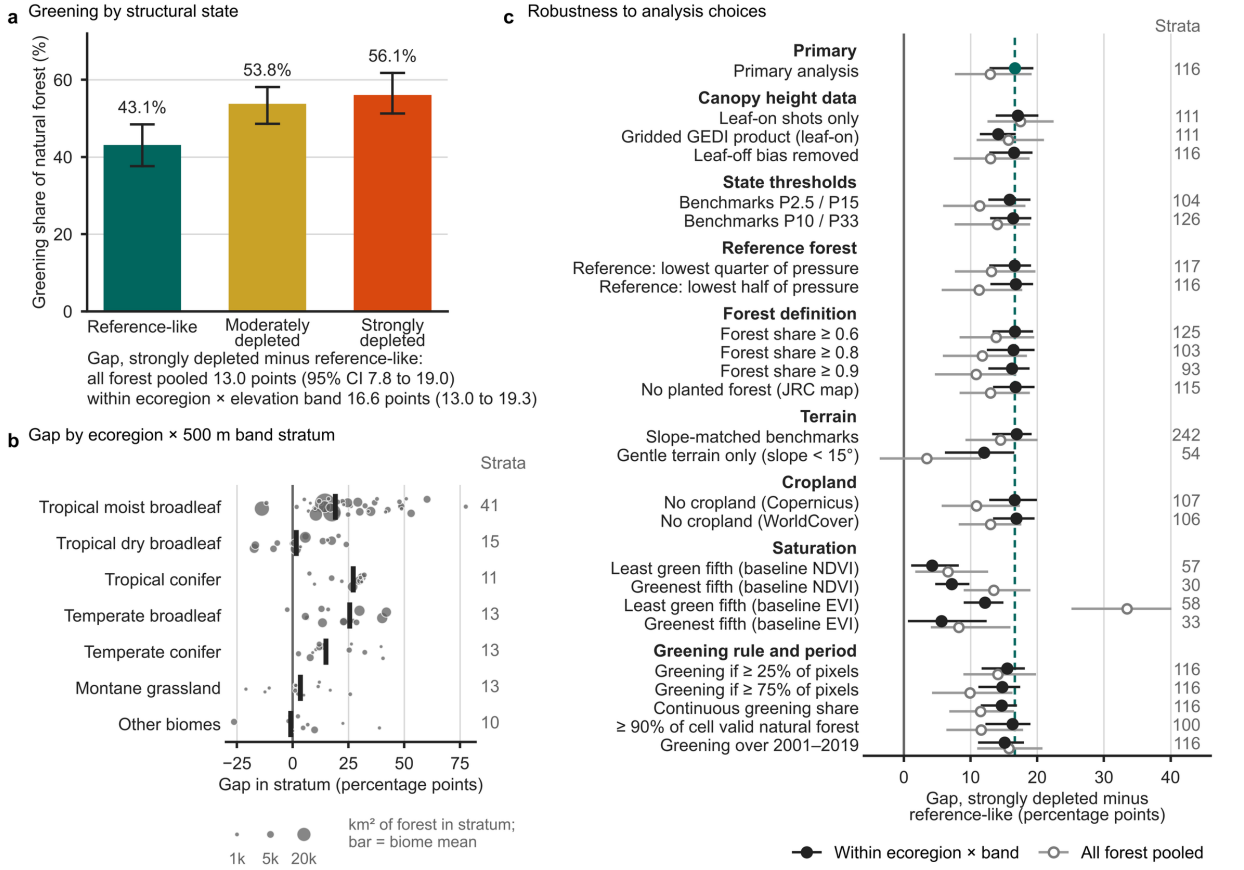


Figure 4. Greening is concentrated in structurally depleted forest: (a) Greening share of natural forest by structural state. (b) Greening gap in each ecoregion × 500 m band stratum, grouped by biome (other biomes: deserts and xeric shrublands, tropical grasslands and savannas, mangroves, and coastal cells outside the ecoregion polygons); biome means are area-weighted. (c) The gap with one analysis choice changed at a time (Methods); dashed line, primary within-stratum estimate. Error bars, 95% confidence intervals from a spatial block bootstrap that re-estimates benchmarks in every replicate.

This pattern was consistent across most forest types and countries (Figure 4b; Table 1). Within strata, the gap averaged 27 points in tropical conifer forest, 26 in temperate broadleaf forest, 19

in tropical moist broadleaf forest and 15 in temperate conifer forest. The exceptions, with no meaningful gap, were tropical dry broadleaf forest (1.5 points) and montane grassland and shrubland (3.4). Among countries, the gap was largest in Nepal (24.3 points; 18.5–27.2) and Bhutan (23.6; 11.8–35.9), followed by India (14.9; 11.4–17.7). It was small in Pakistan (4.4; 0.1–10.9), where forest covers little of the woody domain. Bangladesh and Sri Lanka had too few strata (4 and 3) for a country estimate.

The concentration of greening in depleted forest did not depend on how greening or structure was measured (Figure 4c; Table S5). Across 24 alternative specifications, the confidence interval of the within-stratum gap excluded zero in every case, and choices of canopy-height data, benchmark percentiles, reference forest, forest definition, cropland exclusion, greening rule and greening period kept the gap between 14 and 17 points. Measuring greening over 2001 to 2019, a record that ends in the first year of GEDI observations, gave a gap of 15.1 points (11.3–17.8), although greening was less common in every state (22% of reference-like and 38% of strongly depleted forest). Matching benchmarks on slope, which limits the inflation of GEDI heights on steep terrain that our UAV LiDAR benchmark in Kaski, Nepal, documented,[41] gave 16.9 points. The gap was smaller but still positive on gentle terrain (12.0 points) and in the least or most green fifth of forest (4 to 12 points), which rules out saturation of NDVI in dense canopies as its cause. Cells with a forest share of at least 0.9 gave 16.2 points and the continuous share of greening pixels 14.7, so the result is not an artifact of mixed 1 km cells. Errors in canopy height are also unlikely to create the gap, because states are ranks relative to reference forest of the same stratum. Errors that change steadily with height leave every state unchanged, and random errors blur the contrast rather than produce it. Adding 4.3 m of random error to every cell, the largest cell-level error we could document, reduced the gap to 12.6 points (Figure S1).

Depleted forest carries a longer history of disturbance

If structurally depleted forest reflects past disturbance, and not naturally short stands or measurement error, it should coincide with disturbance recorded by an independent method. We tested this with the JRC Tropical Moist Forest dataset, which maps disturbance since 1990 from Landsat without using LiDAR.[26] Within the moist forest it covers (107,016 km^2, 21.8% of assessed natural forest), the share of each cell that had remained undisturbed since 1990 fell from 51% in reference-like forest to 39% in moderately depleted and 27% in strongly depleted forest (Figure 5a; Table S7). Within ecoregion and elevation strata, strongly depleted forest had 21.3 points less undisturbed area than reference-like forest (16.8–25.0), a difference found in

98% of 42 strata. It also had more area disturbed during the 1990s (7.7 points), more deforested area (9.1 points) and more regrowing forest (4.7 points), but no more area mapped as degraded (0.2 points).

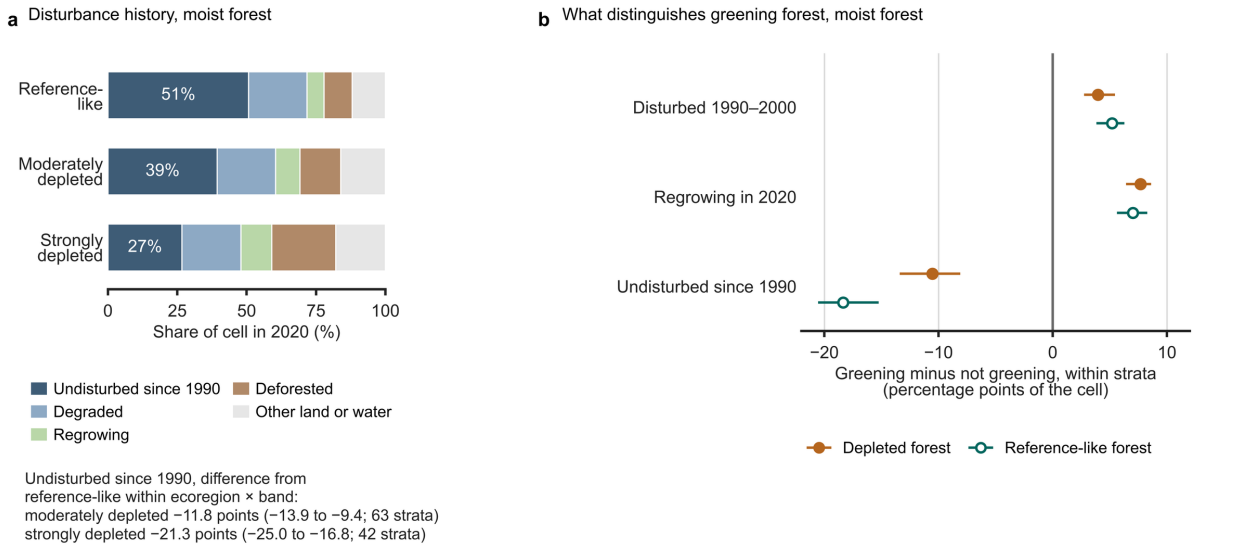


Figure 5. Depleted forest carries a recorded disturbance history, and greening there marks regrowth after disturbance: (a) Condition in 2020 of tropical moist forest by structural state, from the JRC Tropical Moist Forest record (Landsat, 1990 to 2020), which uses no GEDI data and so checks the states independently. (b) Within-stratum differences between greening and not-greening moist forest, for depleted (35 strata) and reference-like forest (48 strata); not-greening forest is almost entirely forest with no majority trend (browning < 1%). Error bars, 95% confidence intervals from a spatial block bootstrap.

Greening depleted forest is regrowing after disturbance

If greening in depleted forest marks regrowth, it should coincide with regrowth after earlier disturbance. Within strata, greening depleted moist forest had 7.7 points more regrowing forest than depleted forest that was not greening (6.5–8.5; higher in all 35 strata), 3.9 points more area disturbed in the 1990s (2.8–5.4), before the greening record begins, and 10.5 points less area undisturbed since 1990 (8.2–13.3) (Figure 5b; Table S7).

Greening reference-like cells also had more regrowth (7.0 points), more disturbance in the 1990s (5.2 points) and less undisturbed area (18.4 points less) than reference-like cells that were not greening (Figure 5b). Greening therefore tracks the return of leaves after disturbance in forest of every state. Because browning covered less than 1% of natural forest (0.8%), forest that was not greening was almost entirely forest with no majority trend, and these contrasts compare greening with stable forest, not with declining forest.

The carbon cost of depleted structure

The structural deficit of greening forest is large in carbon terms (Figure 6). Greening strongly depleted forest had a median canopy height 0.59 times the reference median, and a median aboveground biomass 0.46 times the reference mean, of its stratum; for greening moderately depleted forest the values were 0.78 and 0.66 (Figures 6a and 6b). Across South Asia, assessed natural forest held 3,350 Tg C of aboveground carbon, 592 Tg C (95% confidence interval 475–740) or 15% less than it would if every cell held the reference mean of its stratum (Figure 6c; Table S8). This deficit is the shortfall of depleted forest (742 Tg C, 435 Tg C of it in strongly depleted forest) less the surplus of reference-like forest (150 Tg C). Greening forest covered 49% of the assessed area but held 60% (54–65) of the deficit. Relative to the carbon each would hold at reference biomass, greening forest lacked 23% and other forest 10%, and within strata the difference was 12 percentage points (9–14). India accounted for 445 Tg C (343–587), 59% of it in greening forest. Biomass is estimated from the same LiDAR waveforms as canopy height, so the carbon deficit expresses the structural deficit in carbon units and is not independent evidence of depletion; its division between greening and other forest, however, uses no height threshold.

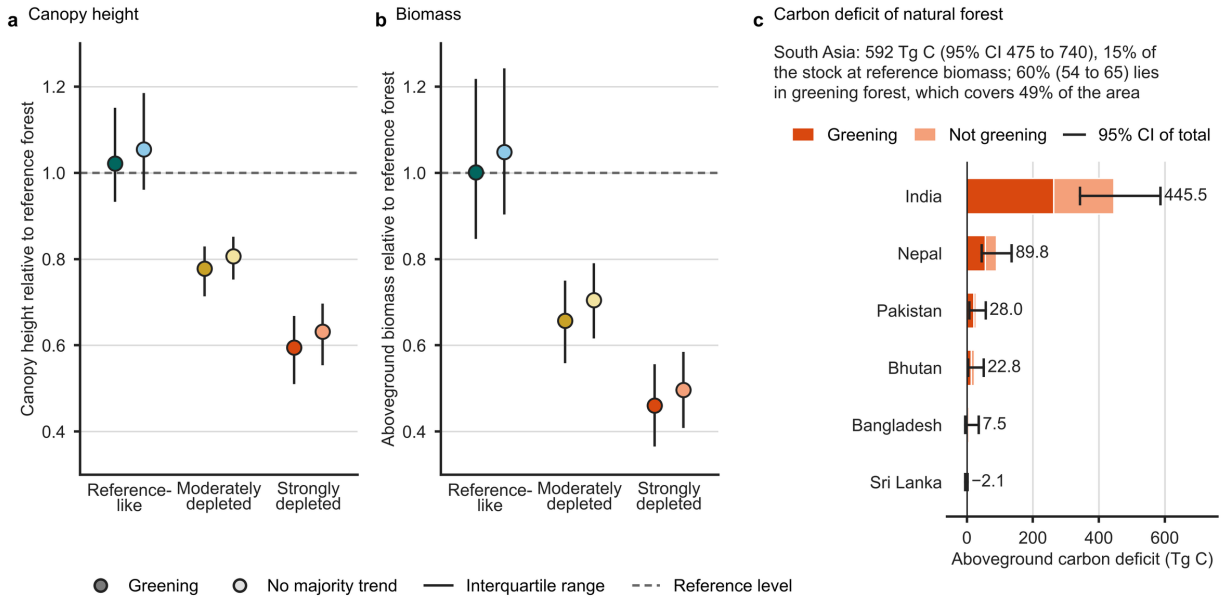


Figure 6. Depleted forest lacks height and biomass, and greening forest holds more than its share of the carbon deficit: (a) Canopy height (GEDI RH98) of natural forest relative to the median of reference forest in the same stratum; markers, area-weighted medians. (b) Aboveground biomass (GEDI L4A) relative to the reference mean of the same stratum. (c) Aboveground carbon deficit of assessed natural forest by country, relative to the reference mean of each stratum and net of forest above it, with confidence intervals from a spatial block bootstrap; a negative value (Sri Lanka) means more carbon than at reference biomass. Biomass comes from

the same LiDAR waveforms as height, so (b) and (c) restate the structural deficit as biomass and carbon.

Discussion

South Asia's forest greening is better explained as regrowth after disturbance than as a general increase in forest growth, and all three predictions of that interpretation were supported. Within the same ecoregion and elevation band, strongly depleted forest was 17 percentage points more likely to be greening than reference-like forest, and more than half of greening natural forest was depleted. An independent Landsat record showed that depleted forest carries a longer history of disturbance and that greening depleted forest is regrowing after it. Across GEDI's near-global coverage, naturally regenerating forest left unmanaged comes closer to intact canopy structure than managed or planted forest, although its structure is lower where tree cover was lost in earlier years and is more strongly influenced by climate, human modification and fire.[42] Some of South Asia's regrowing forest may therefore yet recover; our data show only that it remains structurally depleted today.

Why depleted forest greens

Forest ecology predicts this mismatch between leaves and height in regrowing forest. Canopy cover can return within about 15 years of disturbance,[10] whereas forest structure needs several decades and biomass more than a century to approach old-growth values.[11] LiDAR studies of tropical moist forest show a similar asymmetry, with regrowing forest plateauing at about 60% of intact canopy height after 10 to 15 years and logged and burned forest recovering little height within 20 years.[34] A forest disturbed in the 1990s would therefore be greening throughout our record while remaining low, which matches the disturbance record (Figure 5) and the low GEDI heights of greening depleted forest (Figure 6a). Canopy simplification and NDVI saturation could also create such a gap, but neither fits the data. Canopy simplification raises EVI by reducing shadow,[16,43] whereas our greening rule also required NDVI to increase, and saturation of NDVI, which could make dense, tall forest appear stable, cannot explain a gap that persisted in both the least and the most green forest.

In South Asia, chronic disturbance could keep regrowing forest in this state. Fuelwood cutting has long been identified as the main cause of forest loss and thinning in India.[22] Together with lopping for fodder and the cutting of construction timber, it removes large stems, while grazing and fire prevent fire-sensitive species from reaching the canopy; in the dry deciduous forest of central India, these pressures alter size structure and composition even where forest cover persists.[18,19] Because lopped and cut trees resprout, repeated harvest can renew leaf area

without allowing height to accumulate. Invasive shrubs add leaves beneath a thinned canopy. *Lantana camara* is most abundant in disturbed forest with lopped trees and declining productivity,[21] fire may facilitate its invasion while *Lantana* in turn fuels fire and suppresses regeneration,[44] and invasive species can arrest succession altogether.[11] Stands of this kind can appear as green in satellite records as tall forest while offering less canopy habitat and, probably, weaker buffering of the understory against heat, both of which depend on canopy structure.[12,13]

Pathways to greening in depleted forest

Greening was concentrated in depleted forest even where little forest was depleted. In Bhutan, 64% of assessed forest was reference-like and only 17% of woody vegetation greened, yet the gap within strata (23.6 points) was second only to that in Nepal (24.3 points). The landscapes with the most greening depleted forest point to distinct pathways. In the Kangra Valley of Himachal Pradesh (Figure 3b), four-fifths of forest with a structural state was greening depleted forest, nearly all of it strongly depleted. There, decades of tree planting inside existing forest did not raise canopy cover and shifted composition from broadleaf species toward needleleaf pine.[28] In Mizoram (Figure 3f), the fine mosaic of depleted and reference-like cells resembles the landscape that shifting cultivation creates, in which cultivated fields and fallows of every age are interspersed.[20]

Studies in Nepal suggest pathways in which protection and social change produce regrowth. Its more than 18,000 community forests reduced deforestation between 2000 and 2012 relative to comparable areas without community management.[45] Over the same period, international out-migration was associated with reforestation, most strongly on gentler slopes where households farmed less.[46] Mapped tree cover rose from 26% to 45% of Nepal's land area between 1992 and 2016.[47] Community management and farmland abandonment would both produce young, regrowing forest, which our data record as greening but depleted. One hypothesis consistent with these findings is that community management protected canopy cover while continued harvest of fuelwood and fodder held stands below reference height. None of these studies could measure the condition of the forest that returned,[45–47] and although our data cannot separate these pathways, canopy height relative to reference forest supplies that missing measure.

Revisiting India's greening

These results bear directly on the most widely cited account of India's greening.[2] Where the two analyses overlap, they agree that forest greening is extensive. Our domain excluded cropland mosaics by design, and Indian natural forest greened over 52% of its area between 2001 and

2024 and 28% between 2001 and 2019, against the 47% that Chen et al. reported for Indian forests between 2000 and 2017. The difference lies in what that greening is taken to mean. Chen et al. judged the forest contribution minor because forests supplied 4.4% of the national increase in leaf area, a total dominated by intensively irrigated and fertilized cropland, although a small share of a leaf-area total does not make forest greening minor in extent.

Leaf area is also an incomplete currency for forests, whose carbon and habitat value lie largely in their structure. Chen et al. described greening land as becoming more productive. In forest, however, greening was concentrated where canopy height and biomass were lowest relative to reference forest. Greener forest may photosynthesize more, but greening strongly depleted forest had a median aboveground biomass 0.46 times the reference mean of its stratum (Figure 6b), and model-based estimates even suggest that carbon uptake per unit leaf area in Indian forests declined between the 2000s and the 2010s.[48] For forests, our results support the attribution of India's greening to land-use management in a specific sense, in which human use has depleted forest structure and much of the greening is regrowth within it.

This reasoning also revises our own earlier reading of Himalayan greening, which we attributed to carbon dioxide fertilization and nitrogen deposition because land cover in greening areas appeared unchanged.[49] Chronic use and regrowth leave land cover unchanged, however, and structural data now show that much of that greening forest is depleted, which argues against a reading based purely on fertilization.

The dry forest exception

Tropical dry broadleaf forest was the one major forest type without a gap (1.5 points within strata), and two features of these forests may explain why. Deciduousness in central India rises and falls with rainfall,[50] so annual greenness may track the monsoon more closely than structure. Much of what maps call dry forest is also open, savanna-like vegetation. Structure alone cannot separate a wooded mesic savanna from a degraded forest,[51] and 42% of India's semi-arid open natural ecosystems fall within the dry broadleaf forest biome of the ecoregion map we used to stratify.[52] Reference heights in these strata therefore mix naturally open and degraded stands, which blurs the contrast between states.

Woody gain in these systems should also not be read as restoration. Open natural ecosystems cover about a tenth of India, yet they are often classed as wasteland and targeted for tree planting,[15,52] and much of the recent woodland gain outside India's government forest land is likely to be timber and tree-crop plantation.[27] Assessing the structure of dry forest will require reference sets that separate naturally open woodland from degraded forest.

Implications for restoration and carbon accounting

These findings matter because forest commitments are measured largely by area, cover and greenness. India reports that 21.76 million hectares have been brought under restoration toward its Bonn Challenge pledge of 26 million hectares.[5] If restoration is credited by area, tree cover or greenness, greening depleted forest would count as restored, although its canopy remains well below that of reference forest. NDVI trends at Pakistan's Billion Tree Tsunami sites have already been read in this way.[7] Under SDG 15.3.1, the same forest would also be scored as potentially improving land wherever its NDVI trend is significant, even though the indicator's own guidance warns that rising productivity does not necessarily mean better land condition;[3,4] canopy height relative to reference forest offers a direct test of that warning for forests within GEDI's coverage.

The carbon deficit also adds a LiDAR-based, regional estimate to global ones. Global syntheses place 61% of the carbon that forests could still store in existing forest,[53] attribute 42% to 47% of the vegetation carbon lost to land use to management without land-cover change, including grazing,[54] and estimate that releasing forests from management would add about 44 Pg C aboveground.[55] These estimates are not reported for South Asia. Comparisons of protected with matched unprotected forest have estimated such deficits from GEDI biomass,[56] and our benchmarks apply the same logic to all natural forest, against least-disturbed forest of its kind, and locate the deficit: greening forest covers 49% of assessed natural forest but holds 60% of its carbon deficit.

India has also committed to an additional sink of 2.5 to 3 billion tonnes of CO_2 equivalent through additional forest and tree cover by 2030.[6] India's natural forest lacks 445 Tg C of aboveground carbon relative to reference forest, about 1.6 billion tonnes of CO_2 equivalent (1.3–2.2), of the same order as that target, and 59% of the deficit lies in forest that is already greening. By comparison, restoring forest on the land that remains feasible in India, together with agroforestry on farmland, could add about 160 Tg C,[57] all of it outside existing forest and about a third of the carbon missing from standing natural forest. Neither comparison is direct, because the deficit is a missing stock that would take decades to restore, but together they suggest that the largest forest carbon opportunity in India may lie in allowing depleted forest to recover.

National forest monitoring should therefore report structure alongside cover and greenness. Spaceborne LiDAR measures canopy height at the scale of national reporting, and reference benchmarks make heights comparable between forest types. Greening depleted forest also

marks where regrowth is already under way, and protecting it from renewed disturbance may recover more carbon, sooner, than planting, which in the Indian Himalaya has not raised canopy cover.[28] Claims of forest recovery that rest on greening or tree cover, whether in Bonn Challenge reports, nationally determined contributions or SDG 15.3.1, should be tested against structural data before they enter restoration or carbon accounts.

Limitations of the study

Several limitations should guide interpretation of our results. First, structural states describe 2019 to 2023, whereas greening trends span 2001 to 2024, so we infer from a contemporary snapshot and could not measure whether greening forest is gaining height. GEDI observations began in 2019, and the Landsat-based canopy height maps for 2000 and 2020 cannot resolve changes of a few meters, as their developers caution.[58] Greening measured over 2001 to 2019, almost entirely before the GEDI record, was concentrated in depleted forest to a similar degree, but it was less extensive than over 2001 to 2024, and how much of the additional greening detected when the years after 2019 are included reflects the drift of Terra's overpass time, and how much reflects real change, remains unresolved. Repeated LiDAR from GEDI, its successors and airborne surveys will allow height change to be measured directly. Second, reference forest is the least-disturbed forest that remains and is itself partly disturbed. Forest-loss maps miss selective logging and other degradation,[25,26] and our reference criteria did not screen for fire or grazing, so depletion is likely to be underestimated. Conversely, soil, moisture, aspect, species composition and stand age vary within an ecoregion and elevation band, so some forest classed as depleted may be naturally short; slope-matched benchmarks address terrain only, which is why we report depleted area against the share expected from reference variability. Third, GEDI overestimates canopy height on steep terrain and in open canopies, as our UAV LiDAR benchmark in the Nepal Himalaya showed,[41] which would move depleted cells toward reference-like, and the state of an individual cell is uncertain in steep terrain; our conclusions therefore rest on area-weighted contrasts within strata rather than on individual cells. GEDI biomass is less certain still: the L4A models rest on few calibration plots in continental Asia,[59] and in Indian tropical dry forest L4A biomass had an RMSE of 46% against an airborne LiDAR biomass map,[60] so the carbon totals are less certain than the percentage deficit and its split between greening and other forest, neither of which a proportional bias would change. Fourth, the independent disturbance record covers moist forest only, about a fifth of assessed forest, and our domain excludes woody vegetation within cropland mosaics. Fifth, ForTy maps planted forest least accurately of its classes (F1 scores of 46% for planted and 52%

for plantation forest in Asia), and in India it maps 0.6 Mha of planted forest against a sample-based estimate of 2.8 ± 3.6 Mha,[30] so some plantations are probably counted here as natural forest. When we excluded the 3% of natural forest in which a second forest-type map, from the European Commission's Joint Research Centre,[61] shows any planted forest, the within-stratum gap was 16.7 points (13.6–19.4; Table S5), and the excluded cells showed a smaller gap than the rest; plantations that neither map detects remain a possible source of error. Our results are associations, and depletion and greening arise from many interacting influences, including fire, grazing, rainfall, temperature, access from settlements and forest governance, which remain to be tested together. Plot measurements of size structure and composition are also needed to tell lopped regrowth, fallow and invasion apart where LiDAR shows only a lower canopy.

Conclusions

Satellite greening has become a common measure of environmental progress, from national restoration reports to SDG 15.3.1. For South Asia's forests, that measure needs a structural counterpart, because greening forest there are more often depleted than reference-like and carries a recorded history of disturbance and regrowth. Canopy height relative to the best remaining forest of the same kind provides such a counterpart at national scale, and repeated LiDAR measurements by GEDI and its successors will show which regrowing forests, if protected, regain the height and carbon they have lost. Apart from GEDI, which samples between 51.6° N and 51.6° S, every dataset needed to class greening and structure is global, so the same test can be run for any country within GEDI's coverage.

Methods

Study design

The analysis had two levels on a common 1 km grid. Level 1 asked what vegetation is greening, by combining MODIS greening trajectories for 2001 to 2024 with a global forest typology. Level 2 asked what structure is greening, by classing GEDI canopy height of natural forest relative to least-disturbed reference forest of the same ecoregion and 500 m elevation band. We then tested the structural states and the trajectories of greening forest against an independent Landsat record of disturbance and regrowth, and expressed the structural deficit in carbon units.

Study area and analysis grid

The study covers India, Pakistan, Nepal, Bhutan, Bangladesh and Sri Lanka, and results are reported by the area each country administers. Within Jammu and Kashmir, as delimited in the FAO Global Administrative Unit Layers 2015,[62] cells were assigned to India or Pakistan by the

de facto boundaries of Natural Earth,[63] with the Siachen Glacier assigned to India; Arunachal Pradesh, which India administers, was assigned to India in full. Maps show country boundaries as recognized by India (Natural Earth point-of-view data[63]). Boundaries are used for reporting and display only and imply no position on their status. All layers were aggregated in Google Earth Engine[64] to a common grid of 0.008991° (about 1 km; EPSG:4326). Datasets, versions and access details are listed in Table S1.

The analysis domain comprised 1 km cells with Copernicus Global Land Cover[65] tree and shrub cover of at least 10% and cropland below 10%, excluding rock and ice (912,687 km^2; 1,006,864 cells). The cropland criterion excludes woody vegetation within farmland, where MODIS pixels mix tree and crop signals. It removed 18% of ForTy natural forest, 55% of planted forest and 63% of tree-crop area. Woody 250 m pixels in excluded cells greened more often than those inside the domain (74% against 51%), and greening rose smoothly with a cell's cropland share, with no discontinuity at the threshold. Our results therefore describe woody vegetation outside cropland mosaics and do not address greening of trees on farms.

Vegetation types

Vegetation type came from the global forest typology ForTy 2020 (10 m),[30] aggregated to the shares of each 250 m MODIS pixel and each 1 km cell. ForTy distinguishes natural forest (primary and naturally regenerating), planted forest (planted and plantation forest) and tree crops. A 1 km cell was classed as natural forest when natural forest covered at least half of it, as planted forest when planted forest did, and as mixed forest when forest covered at least half but neither type did; otherwise it was classed as tree crops when tree crops covered at least half, and as shrub, scrub and open woodland in all remaining cases. Mixed forest covered 0.2% of the domain and was grouped with natural forest in Level 1. The shrub, scrub and open woodland class includes thorn scrub, savanna and other open natural ecosystems that are not degraded forest.[51,52] The structural analysis used natural-forest cells with a forest share of at least 0.7 (reference cells, below, required a natural-forest share of at least 0.7); cells with 50% to 70% forest were reported as open forest mosaic.

Greening trajectories

We used MODIS Terra vegetation indices (MOD13Q1, Collection 6.1, 250 m, 16-day composites[66]) for 2001 to 2024. For each pixel and year we averaged NDVI and EVI over composites flagged good or marginal in the quality layer, filling missing composites with the pixel's long-term mean for that 16-day slot; a year required at least eight real composites, and a pixel required valid data in at least 75% of years. We used annual means rather than a growing-

season window because South Asia has two monsoons and widespread deciduous forest whose leaf-off phase is part of the signal.[50] Trends were Sen slopes.[67] A pixel was greening when both the NDVI and EVI slopes exceeded +0.001 yr^{-1}, browning when either fell below −0.001 yr^{-1}, and stable otherwise. Requiring both indices guards against EVI artifacts from canopy shadowing and sun-sensor geometry in complex canopies,[16,43] because NDVI and EVI are partly independent measurements.[9]

Each 1 km cell took the trajectory of its own vegetation type: the share of its 250 m pixels of that type that were greening or browning. A cell was greening (or browning) when that share was at least 0.5, and otherwise had no majority trend. Shares of the domain in Level 1 are pixel-weighted (the greening share times the cell area), and areas of trajectories by structural state use the majority rule; the two differ slightly. Areas are map-based and not adjusted for classification error.[68]

Terra's overpass time has drifted since 2020, which can bias trends in geometry-sensitive indices. We therefore repeated the analysis with trends for 2001 to 2019, with the same rules (valid data in at least 15 of 19 years) and the vegetation types and structural states of the primary analysis. This record ends in 2019, the year GEDI began acquiring data, so greening is measured almost entirely before structure.

Canopy height from GEDI

Canopy height was the relative height at which 98% of waveform energy is returned (RH98) in GEDI L2A Version 2 footprints[33,69] from 17 April 2019 to 17 March 2023. We kept shots with quality flag 1, degrade flag 0 and beam sensitivity of at least 0.95, and aggregated them directly from the shot tables to the 1 km grid as the median RH98 of all shots in each cell. A cell had a valid height when it held at least 10 shots and its median lay between 4 and 60 m.

Unlike the gridded GEDI product,[70] we kept leaf-off shots. In South Asia's deciduous forest the cloud-free shots are mostly from the dry season, so a leaf-on filter left 37% of forest without a valid height, concentrated in tropical moist and dry deciduous forest. In 614 cells with at least three leaf-on and three leaf-off shots over pure, unlogged natural forest on slopes below 35°, the median difference in RH98 between leaf-off and leaf-on shots was −0.11 m (−1.0%). Including leaf-off shots raised the share of forest with a valid height from 62.6% to 88.2%. Our leaf-on heights reproduced the gridded product where both had data (median differences of +0.04 and +0.09 m in two test regions in central India and Bhutan). Results with leaf-on shots only, with the gridded product and with leaf-off heights corrected for the small biome-specific bias are reported as robustness checks (Figure 4c; Table S5).

Aboveground biomass

Aboveground biomass density came from GEDI L4A Version 2.1 footprints,[59,71] filtered as for height (leaf-off shots retained), averaged per 1 km cell (at least 10 shots). The L4A models for deciduous forest are calibrated on leaf-on airborne LiDAR, and leaf-off shots read 4% to 12% low by biome (ratio of leaf-off to leaf-on means 0.902 over all forest, in cells with at least five of each). We divided the leaf-off part of each cell's mean by its biome ratio; in cells with many shots of both kinds, this brought all-shot biomass to within 0.3% of leaf-on biomass. Biomass estimates are weakest in continental Asia, where calibration plots are sparse,[59] so biomass is used to express the structural deficit in carbon units, not to class structure.

Reference forest and structural states

Following the reference-condition approach,[37] reference forest was the least-disturbed natural forest available today, selected with pressure criteria alone and without using structure, greenness or protection status. Reference cells had a natural-forest share of at least 0.7, forest loss of no more than 1% in 2001 to 2023 (Hansen Global Forest Change v1.12[25]), WorldCover cropland of no more than 5%,[72] and population density (GHS-POP 2020[73]) and nighttime lights (VIIRS 2022 to 2024[74]) in the lowest third of natural-forest cells in the same ecoregion. Of 609,480 natural-forest cells, 143,715 met these criteria and 125,533 had a valid height (Figure 1d).

Strata were RESOLVE ecoregions[75] crossed with 500 m elevation bands from the Copernicus 30 m digital elevation model.[76] Benchmarks were the 5th and 25th percentiles of reference RH98 in each stratum with at least 30 reference cells (Table S3); otherwise the ecoregion, then biome by elevation band, then biome was used. Of forest area, 98.5% was benchmarked in its own stratum. Cells at or above the 25th percentile were reference-like, cells between the 5th and 25th percentiles moderately depleted, and cells below the 5th percentile strongly depleted. These classes are operational: by construction, a quarter of reference forest falls below its 25th percentile and 5% below its 5th, so we also report the depleted share in excess of 25% and the strongly depleted share as a multiple of 5%, with confidence intervals from the spatial block bootstrap described below, under every analysis choice (Table S5). Comparing structure with intact forest of the same region follows Bourgoin et al.[34] Because selective logging, fuelwood collection, grazing and fire are not captured by forest-loss maps,[25,26] and our criteria did not screen for fire or grazing, reference forest is least disturbed rather than undisturbed, and depletion is measured conservatively.

Statistical analysis

Greening shares by state were area-weighted over natural forest with a structural state. The pooled gap was the greening share of strongly depleted forest minus that of reference-like forest. The within-stratum gap was the same difference computed in each ecoregion and elevation band stratum with at least 20 cells of each state, averaged with weights equal to the stratum's assessed forest area (stratum estimates in Table S6). Confidence intervals came from a spatial block bootstrap that accounts for spatial autocorrelation:[77,78] 1° blocks were resampled with replacement, and in every replicate the reference benchmarks were recomputed from the resampled reference cells and all states were reassigned, so the intervals include uncertainty in the benchmarks. We used 1,000 replicates for the primary analysis and 300 for each robustness specification, and report percentile intervals.

The robustness specifications (Figure 4c; Table S5) changed one choice at a time: the canopy-height data (leaf-on shots only; gridded GEDI product; leaf-off heights corrected by biome); the benchmark percentiles (2.5th and 15th; 10th and 33rd); the pressure quantile defining reference forest (lowest quarter; lowest half); the forest definition (minimum forest share of 0.6, 0.8 or 0.9; or no planted or plantation forest in the cell in the JRC Global Forest Types 2020 map[61]); terrain (benchmarks matched on slope class of below 10°, 10° to 20°, 20° to 30° and 30° or more within ecoregion and band; or reference and assessed cells restricted to slopes below 15°); cropland (cells with no Copernicus or no WorldCover cropland); saturation (least or most green fifth of cells by 2001 to 2005 baseline NDVI or EVI); the greening rule (at least 25% or 75% of a cell's natural-forest pixels greening; the continuous share of greening pixels; cells in which at least 90% of pixels were natural forest with a valid trend); and the greening period (2001 to 2019).

Sensitivity to canopy-height error

Structural states are percentile ranks relative to reference cells of the same stratum. Any error that is an increasing function of true height, including a common offset and GEDI's compression of short and tall canopies, therefore preserves ranks and leaves every state unchanged. We confirmed this by applying to every cell the calibration line between GEDI RH98 and UAV LiDAR canopy height from our benchmark of 391 footprints in steep forest in Kaski, Nepal[41] (UAV height = 8.50 + 0.537 × RH98; state agreement 100%). In that benchmark, RH98 exceeded the UAV LiDAR 98th percentile height by 2.4 m on average (root-mean-square error 8.5 m per shot). Where the matched footprints fell in our 1 km cells, the median of matched GEDI shots differed from the median UAV height of the same footprints with a standard deviation of 4.3 m after removing the mean offset. This value comes from the steepest terrain in

the domain (mean slope about 37°), and the matched shots cover only part of each cell, so we treat it as an upper bound.

Random error moves cells across state boundaries. We added Gaussian error with standard deviations from 1.4 to 6.1 m to every cell's RH98, recomputed benchmarks and states, and recalculated the gaps (60 replicates per level; Figure S1). If errors were unrelated to greening, this blurring could only reduce the gap. One plausible link runs in the conservative direction: GEDI overestimates the height of open canopies in our benchmark,[41] which moves open depleted cells toward reference-like.

Disturbance history

We used the JRC Tropical Moist Forest dataset (version 2025[26]), aggregated to the 1 km grid as shares of 30 m pixels: the share of each cell that was undisturbed, degraded, deforested or regrowing in December 2020, and the share that was undisturbed in 1990 and disturbed by 2000. This dataset covers tropical moist forest only, so these analyses were restricted to cells in which at least half the area was tropical moist forest in 1990 (107,016 km^2, 21.8% of assessed natural forest; 67% in India, 17% in Bhutan, 9% in Sri Lanka, 5% in Bangladesh and 2% in Nepal). We did not estimate canopy height change from the Landsat-based GLAD forest height maps for 2000 and 2020,[58] because their developers caution that small differences between the two maps may reflect model noise and that direct comparison without their change thresholds does not give consistent results; those thresholds record only forest establishment, a doubling or halving of height, and forest loss, which cannot resolve the few meters of growth at issue here.

We compared structural states (strongly or moderately depleted minus reference-like) and trajectories (greening minus not greening, within depleted or within reference-like forest) with the within-stratum estimator described above (at least 20 cells of each group; Table S7), with confidence intervals from 1,000 spatial block bootstrap replicates in which benchmarks and states were re-estimated. The Tropical Moist Forest dataset uses no LiDAR data, so the state comparison is independent of GEDI. Regrowth in this record is partly linked to optical greening by construction, whereas 1990s disturbance precedes the MODIS record.

Carbon deficit

For each natural-forest cell with a structural state, valid biomass and a MODIS trajectory (99.8% of assessed natural forest by area), the carbon deficit was (reference mean biomass of its stratum − cell biomass) × area × 0.47, the default carbon fraction of dry biomass.[79] We summed

cell deficits over all assessed natural forest, whatever its structural state and without truncation, so cells with more biomass than the reference mean offset those with less, and reference forest itself has a net deficit of about zero. We did not sum depleted cells alone, because a quarter of reference forest itself falls in the depleted classes: that sum is 742 Tg C, and it would still be 315 Tg C if all assessed forest had reference structure, whose net deficit is zero (estimated, stratum by stratum, as the shortfall of reference cells classed as depleted per unit area of all reference cells, times assessed area). The percentage deficit of greening and other forest was compared within strata with at least 20 cells of each, averaged with area weights. With leaf-on biomass alone, the deficit was 14.5% of the stock at reference biomass and the within-stratum difference 12.1 percentage points. Reference biomass was computed in the same strata, from the same reference cells and with the same fallbacks as height benchmarks. Confidence intervals came from 500 spatial block bootstrap replicates in which reference biomass, benchmarks and states were re-estimated (Table S8); they do not include the error of the L4A biomass models.

Software and use of AI-assisted tools

Google Earth Engine (JavaScript) was used to compute per-pixel Theil–Sen trends in annual MODIS NDVI and EVI, to filter GEDI L2A and L4A shots, and to aggregate every input to the 1 km grid, including the share of each cell's MODIS pixels that was greening in each vegetation type. All other analyses were done in Python 3.13 with NumPy, pandas, SciPy and Matplotlib. The authors used Microsoft Copilot to assist with literature review searches, language proofreading and clarity improvement. The authors take full responsibility for the final manuscript.

Data and code availability

The Level 1 and Level 2 maps, with summaries by country, ecoregion and Indian state, can be explored in the South Asia Greening Explorer, a Google Earth Engine app: https://ee-nbm.projects.earthengine.app/view/south-asia-greening-explorer. All input datasets are publicly available from the sources listed in Table S1. The Google Earth Engine scripts that produce the 1 km layers will be made available on GitHub on publication. Other code used in this study is available from the corresponding author on reasonable request.

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Author contributions

Conceptualization, N.B.M.; methodology, N.B.M. and G.C.; formal analysis, N.B.M. and G.C.; investigation, N.B.M. and G.C.; resources, N.B.M.; visualization, N.B.M. and G.C.; writing – original draft, N.B.M.; writing – review and editing, N.B.M. and G.C.; funding acquisition, N.B.M. and G.C.

Competing interests

The authors declare no competing interests.

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Supplementary information

Figure S1 follows; Tables S1 to S8 follow the figure.

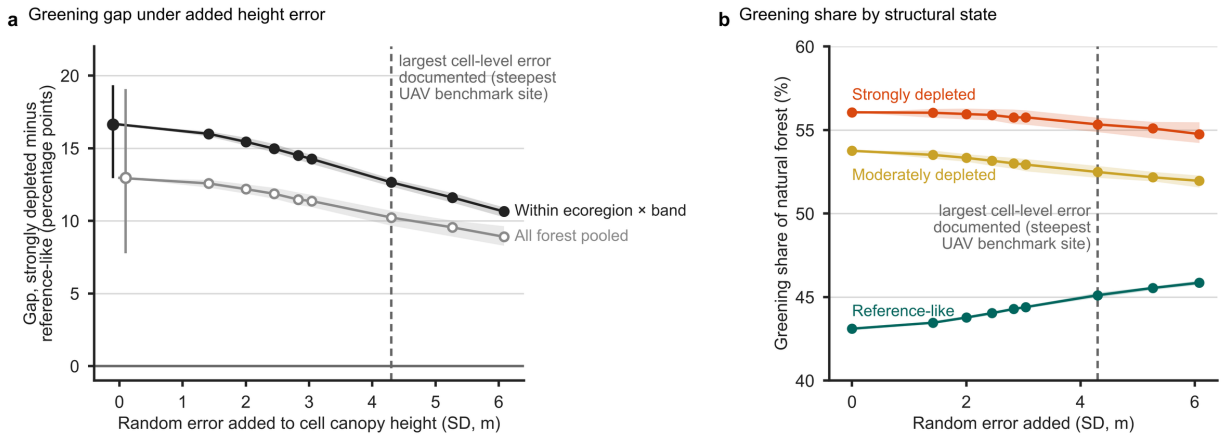


Figure S1. Random error in canopy height blurs the greening gap but does not create it, related to Figure 4.

(a) The greening gap after adding Gaussian random error of the given standard deviation to every cell's canopy height (RH98), with benchmarks and states re-estimated each time; lines, mean of 60 replicates; bands, 2.5% to 97.5% of replicates (variation between noise draws only); at zero, the observed estimate with its 95% bootstrap confidence interval. Dashed line, 4.3 m, the cell-level difference between GEDI and UAV LiDAR canopy heights at our steepest benchmark site in Kaski, Nepal,[41] treated as an upper bound. (b) Greening share of natural forest by structural state under the same perturbations.

Table S1. Datasets used in this study.

Dataset and version	Type, resolution	Period used	Variables used	Use in this study	Reference; access
Analysis domain and vegetation type					
Copernicus Global Land Cover (CGLS-LC100), Collection 3, epoch 2019	Raster, 100 m	2019	Discrete classes: forest (111–126), shrubs (20), cropland (40), as 1 km shares	Woody domain (tree and shrub cover ≥ 10% and cropland < 10% of the 1 km cell); cropland robustness check	Buchhorn et al. (2020); doi:10.5281/zenodo.3939050; EE: COPERNICUS/Landcover/100m/Proba-V-C3/Global/2019
Global forest typology (ForTy) 2020, v1.0	Raster, 10 m	2020	Primary and naturally regenerating (natural); planted and plantation (planted); tree crops	Vegetation type of each 250 m pixel and 1 km cell; forest share ≥ 0.7 for structural states and reference cells	Neumann et al. (2026); doi:10.1038/s41597-026-08299-5; EE: projects/nature-trace/assets/forest_typology/forest_typology_2020_v1_0_classification
JRC Global Forest Types 2020, V1	Raster, 10 m	2020	Planted and plantation forest (class 20), as 1 km shares	Plantation robustness check: cells with any planted forest excluded (Table S5)	Bourgoin et al. (2026); doi:10.2760/9982436; EE: JRC/GFC2020_subtypes/V1
ESA WorldCover 2020, v100	Raster, 10 m	2020	Cropland	Reference cells (cropland ≤ 5%); cropland robustness check	Zanaga et al. (2021); doi:10.5281/zenodo.5571936; EE: ESA/WorldCover/v100
Greenness (Level 1)					
MODIS Terra Vegetation Indices (MOD13Q1), Collection 6.1	Raster, 250 m, 16-day	2001–2024 (2001–2019 sensitivity)	NDVI, EVI, SummaryQA	Annual means of good and marginal observations; Sen slope per 250 m pixel; greening (NDVI and EVI > +0.001 yr^{-1}), browning (NDVI or EVI < −0.001 yr^{-1})	Didan (2021); doi:10.5067/MODIS/MOD13Q1.061; EE: MODIS/061/MOD13Q1
Forest structure and biomass (Level 2)					
GEDI L2A Elevation and Height Metrics, footprint level, V002	Footprints, 25 m	17 Apr 2019–17 Mar 2023	RH98, quality flag, degrade flag, beam sensitivity, leaf-off flag	Cell canopy height: median RH98 of quality shots (quality 1, degrade 0, sensitivity ≥ 0.95), leaf-off shots kept; valid with ≥ 10 shots and median 4–60 m	Dubayah et al. (2021); doi:10.5067/GEDI/GEDI02_A.002; EE: LARSE/GEDI/GEDI02_A_002_INDEX and shot tables
GEDI L4A Footprint Level Aboveground Biomass Density, Version 2.1	Footprints, 25 m	17 Apr 2019–17 Mar 2023	Aboveground biomass density (AGBD)	Cell mean AGBD (≥ 10 shots), leaf-off shots corrected by biome ratio; carbon deficit relative to reference forest	Dubayah et al. (2022); doi:10.3334/ORNLDAAC/2056; EE: LARSE/GEDI/GEDI04_A_002_INDEX and shot tables
Gridded GEDI vegetation structure metrics, V1 (from GEDI L2A V002)	Raster, 1 km	Apr 2019–Mar 2023	RH98 median (leaf-on), shot count	Robustness check (gridded product); check of our leaf-on cell heights	Burns et al. (2024); doi:10.1038/s41597-024-03668-4; EE: LARSE/GEDI/GRIDDEDVEG_002/V1/1KM
UAV LiDAR benchmark of GEDI, Kaski, Nepal	UAV LiDAR point clouds matched to GEDI footprints	Surveyed for Mishra and Singh (2026)	391 matched footprints: UAV LiDAR 98th percentile height and GEDI RH98	Calibration line and error magnitudes for the sensitivity of structural states to canopy-height error (Figure S1)	Mishra and Singh (2026); doi:10.1016/j.jag.2026.105203
Reference-forest selection					
Hansen Global Forest Change, v1.12	Raster, 30 m	2000–2023	Loss year	Reference cells (loss 2001–2023 ≤ 1%)	Hansen et al. (2013); doi:10.1126/science.1244693; EE: UMD/hansen/global_forest_change_2024_v1_12
GHS-POP, release R2023A	Raster, 100 m	2020	Population count	Reference cells (population density in the lowest third of natural-forest cells per ecoregion)	Schiavina et al. (2023); doi:10.2905/2FF68A52-5B5B-4A22-8F40-C41DA8332CFE; EE: JRC/GHSL/P2023A/GHS_POP
VIIRS Day/Night Band monthly composites, stray-light corrected, V1	Raster, 464 m, monthly	2022–2024	Average radiance (median)	Reference cells (nighttime lights in the lowest third per ecoregion)	Elvidge et al. (2017); EE: NOAA/VIIRS/DNB/MONTHLY_V1/VCMSLCFG
Disturbance history					
JRC Tropical Moist Forest, version 2025, annual change collection	Raster, 30 m, annual	1990–2020	Undisturbed, degraded, deforested and regrowing forest in December 2020; undisturbed in 1990; disturbed by 2000	Independent (no LiDAR) test of structural states and trajectories in cells with ≥ 50% moist forest in 1990	Vancutsem et al. (2021); EE: projects/JRC/TMF/v1_2025/AnnualChanges
Stratification, terrain and boundaries					
RESOLVE Ecoregions 2017	Vector polygons	Static	Ecoregion ID, biome	Benchmark strata (ecoregion × 500 m elevation band); rock and ice exclusion	Dinerstein et al. (2017); doi:10.1093/biosci/bix014; EE: RESOLVE/ECOREGIONS/2017
Copernicus DEM GLO-30	Raster, 30 m	Static	Elevation, slope	500 m elevation bands; slope classes and gentle-terrain subset (robustness); slope screen (< 35°) for the leaf-off test	European Space Agency (2021); EE: COPERNICUS/DEM/GLO30
FAO Global Administrative Unit Layers (GAUL) 2015, level 0	Vector polygons	2015	Country units	Delimitation of Jammu and Kashmir for the assignment of cells to administering countries	FAO (2015); EE: FAO/GAUL/2015/level0
Natural Earth, 1:10m cultural vectors, v5.1.1	Vector	June 2022	De facto boundaries; point-of-view boundaries of India	Assignment of cells within Jammu and Kashmir; map boundaries as recognized by India	Natural Earth (2022); naturalearthdata.com

Abbreviations: AGBD, aboveground biomass density; EVI, enhanced vegetation index; GEDI, Global Ecosystem Dynamics Investigation; NDVI, normalized difference vegetation index; RH98, height at which 98% of the LiDAR waveform energy is returned (canopy height).

References (full entries in the main reference list): Bourgoin et al. (2026); Buchhorn et al. (2020); Burns et al. (2024); Didan (2021); Dinerstein et al. (2017); Dubayah et al. (2021, 2022); Elvidge et al. (2017); European Space Agency (2021); FAO (2015); Hansen et al. (2013); Mishra and Singh (2026); Natural Earth (2022); Neumann et al. (2026); Schiavina et al. (2023); Vancutsem et al. (2021); Zanaga et al. (2021).

Table S2. Level 1 vegetation type and trajectory by country (km²), related to Figure 2.

Class	India	Pakistan	Nepal	Bhutan	Bangladesh	Sri Lanka	South Asia
Natural forest, greening	253,442	12,590	28,056	4,419	4,302	7,463	310,272
Natural forest, no majority trend	230,145	7,455	31,343	24,112	11,748	14,063	318,865
Natural forest, browning	3,098	149	682	359	460	146	4,893
Planted forest, greening	1,209	10	204	0	7	25	1,456
Planted forest, no majority trend	736	3	81	0	15	53	887
Planted forest, browning	124	0	2	0	3	0	129
Tree crops, greening	15,271	167	17	1	3,362	3,659	22,477
Tree crops, no majority trend	16,514	68	10	0	1,044	9,461	27,097
Tree crops, browning	1,608	0	1	0	46	178	1,833
Shrub, scrub, open woodland, greening	59,735	74,797	6,335	322	887	2,384	144,461
Shrub, scrub, open woodland, no majority trend	33,902	20,580	6,882	2,258	1,250	3,258	68,131
Shrub, scrub, open woodland, browning	3,237	684	296	122	281	813	5,433
No MODIS trend (too few valid years)	6,354	66	56	237	19	22	6,753
Total	**625,375**	**116,569**	**73,965**	**31,830**	**23,424**	**41,525**	**912,687**

Table S3. Reference canopy-height benchmarks by ecoregion and 500 m elevation band, related to Figure 3. 5th and 25th percentiles (P5, P25) of GEDI RH98 among least-disturbed reference cells (criteria in Methods), per ecoregion × 500 m elevation band. 134 of 214 strata, holding 98.5% of forest area, have ≥ 30 reference cells and their own benchmark.

Ecoregion[a]	Elevation band (m)	Reference cells with height	P5 (m)	P25 (m)	Median (m)	Forest area (km²)	Forest area (% of all forest)	Benchmark source[b]
Tropical and subtropical moist broadleaf forests (biome 1)								
218 Andaman Islands rain forests	below 0	0	–	–	–	3	0.00	fallback
218 Andaman Islands rain forests	0–500	1,411	20.6	27.4	30.9	4,345	0.78	own stratum
218 Andaman Islands rain forests	500–1,000	0	–	–	–	6	0.00	fallback
222 Brahmaputra Valley semi-evergreen forests	0–500	1,014	14.3	18.9	22.4	6,337	1.14	own stratum
222 Brahmaputra Valley semi-evergreen forests	500–1,000	53	21.7	23.7	27.5	679	0.12	own stratum
222 Brahmaputra Valley semi-evergreen forests	1,000–1,500	32	26.8	29.5	33.3	87	0.02	own stratum
222 Brahmaputra Valley semi-evergreen forests	1,500–2,000	6	32.9	34.9	38.2	14	0.00	fallback
226 Chin Hills-Arakan Yoma montane forests	0–500	0	–	–	–	9	0.00	fallback
226 Chin Hills-Arakan Yoma montane forests	500–1,000	0	–	–	–	16	0.00	fallback
226 Chin Hills-Arakan Yoma montane forests	1,000–1,500	3	23.7	27.0	31.1	12	0.00	fallback
226 Chin Hills-Arakan Yoma montane forests	1,500–2,000	0	–	–	–	2	0.00	fallback
228 East Deccan moist deciduous forests	0–500	12,958	11.9	16.0	18.7	50,115	8.99	own stratum
228 East Deccan moist deciduous forests	500–1,000	10,347	12.3	17.0	19.6	38,204	6.85	own stratum
228 East Deccan moist deciduous forests	1,000–1,500	196	13.7	17.0	18.6	868	0.16	own stratum
233 Himalayan subtropical broadleaf forests	0–500	1,313	19.8	24.6	27.9	6,936	1.24	own stratum
233 Himalayan subtropical broadleaf forests	500–1,000	1,947	21.4	26.3	29.6	10,447	1.87	own stratum
233 Himalayan subtropical broadleaf forests	1,000–1,500	282	22.7	27.9	30.4	1,118	0.20	own stratum
233 Himalayan subtropical broadleaf forests	1,500–2,000	19	24.7	28.3	31.6	77	0.01	fallback
233 Himalayan subtropical broadleaf forests	2,000–2,500	3	28.4	29.4	30.6	6	0.00	fallback
233 Himalayan subtropical broadleaf forests	2,500–3,000	38	26.4	28.6	31.8	126	0.02	own stratum
233 Himalayan subtropical broadleaf forests	3,000–3,500	173	18.9	24.3	30.2	232	0.04	own stratum
233 Himalayan subtropical broadleaf forests	3,500–4,000	71	17.2	26.5	31.0	70	0.01	own stratum
233 Himalayan subtropical broadleaf forests	4,000–4,500	3	14.8	16.9	19.6	3	0.00	fallback
238 Lower Gangetic Plains moist deciduous forests	0–500	320	7.4	9.5	11.6	10,087	1.81	own stratum
238 Lower Gangetic Plains moist deciduous forests	500–1,000	9	9.4	9.8	10.6	98	0.02	fallback
242 Malabar Coast moist forests	0–500	286	6.9	9.7	13.6	3,135	0.56	own stratum
242 Malabar Coast moist forests	500–1,000	36	13.4	17.6	24.8	92	0.02	own stratum
242 Malabar Coast moist forests	1,000–1,500	8	11.2	14.6	17.6	9	0.00	fallback
244 Meghalaya subtropical forests	0–500	672	16.8	20.6	23.5	15,530	2.78	own stratum
244 Meghalaya subtropical forests	500–1,000	818	17.9	23.3	26.8	8,412	1.51	own stratum
244 Meghalaya subtropical forests	1,000–1,500	314	18.5	22.7	25.5	1,899	0.34	own stratum
244 Meghalaya subtropical forests	1,500–2,000	32	18.0	21.6	23.3	217	0.04	own stratum
249 Mizoram-Manipur-Kachin rain forests	0–500	1,371	19.4	23.1	25.7	24,149	4.33	own stratum
249 Mizoram-Manipur-Kachin rain forests	500–1,000	856	21.9	25.5	28.2	18,145	3.25	own stratum
249 Mizoram-Manipur-Kachin rain forests	1,000–1,500	511	20.6	25.6	29.3	9,425	1.69	own stratum
249 Mizoram-Manipur-Kachin rain forests	1,500–2,000	433	24.1	29.3	31.8	1,965	0.35	own stratum
249 Mizoram-Manipur-Kachin rain forests	2,000–2,500	234	24.4	29.3	32.1	418	0.07	own stratum
249 Mizoram-Manipur-Kachin rain forests	2,500–3,000	79	19.9	22.0	24.3	81	0.01	own stratum
249 Mizoram-Manipur-Kachin rain forests	3,000–3,500	3	24.3	26.0	28.2	3	0.00	fallback
250 Myanmar coastal rain forests	0–500	0	–	–	–	15	0.00	fallback

Ecoregion[a]	Elevation band (m)	Reference cells with height	P5 (m)	P25 (m)	Median (m)	Forest area (km²)	Forest area (% of all forest)	Benchmark source[b]
252 Nicobar Islands rain forests	0–500	122	23.2	30.4	32.5	1,047	0.19	own stratum
252 Nicobar Islands rain forests	500–1,000	0	–	–	–	2	0.00	fallback
253 North Western Ghats moist deciduous forests	0–500	896	12.8	18.3	21.2	6,833	1.23	own stratum
253 North Western Ghats moist deciduous forests	500–1,000	906	10.1	16.6	20.0	3,030	0.54	own stratum
253 North Western Ghats moist deciduous forests	1,000–1,500	35	6.5	9.1	11.8	319	0.06	own stratum
253 North Western Ghats moist deciduous forests	1,500–2,000	3	8.4	11.7	15.7	3	0.00	fallback
254 North Western Ghats montane rain forests	0–500	768	17.3	22.1	24.8	5,043	0.90	own stratum
254 North Western Ghats montane rain forests	500–1,000	1,418	9.8	15.2	20.1	8,890	1.59	own stratum
254 North Western Ghats montane rain forests	1,000–1,500	108	11.6	17.4	20.6	992	0.18	own stratum
254 North Western Ghats montane rain forests	1,500–2,000	5	13.8	15.1	16.9	10	0.00	fallback
261 Orissa semi-evergreen forests	0–500	386	8.5	12.5	14.6	1,835	0.33	own stratum
261 Orissa semi-evergreen forests	500–1,000	29	14.3	15.9	18.1	49	0.01	fallback
270 South Western Ghats moist deciduous forests	0–500	95	11.2	26.6	29.0	1,782	0.32	own stratum
270 South Western Ghats moist deciduous forests	500–1,000	1,353	8.1	12.2	17.0	4,129	0.74	own stratum
270 South Western Ghats moist deciduous forests	1,000–1,500	556	9.9	15.2	19.7	1,383	0.25	own stratum
270 South Western Ghats moist deciduous forests	1,500–2,000	136	15.0	19.0	21.4	233	0.04	own stratum
270 South Western Ghats moist deciduous forests	2,000–2,500	2	20.8	20.9	21.0	26	0.00	fallback
271 South Western Ghats montane rain forests	0–500	176	22.1	26.7	29.6	2,335	0.42	own stratum
271 South Western Ghats montane rain forests	500–1,000	824	19.8	25.3	28.5	4,487	0.80	own stratum
271 South Western Ghats montane rain forests	1,000–1,500	778	18.2	23.3	27.2	2,628	0.47	own stratum
271 South Western Ghats montane rain forests	1,500–2,000	201	16.2	19.4	22.8	524	0.09	own stratum
271 South Western Ghats montane rain forests	2,000–2,500	53	12.1	17.0	18.9	418	0.07	own stratum
274 Sri Lanka lowland rain forests	0–500	126	15.5	18.4	20.4	1,165	0.21	own stratum
274 Sri Lanka lowland rain forests	500–1,000	119	14.7	18.4	22.0	934	0.17	own stratum
274 Sri Lanka lowland rain forests	1,000–1,500	9	18.6	24.2	27.7	112	0.02	fallback
275 Sri Lanka montane rain forests	0–500	1	26.2	26.2	26.2	16	0.00	fallback
275 Sri Lanka montane rain forests	500–1,000	11	16.6	18.6	23.0	166	0.03	fallback
275 Sri Lanka montane rain forests	1,000–1,500	47	14.1	18.4	26.1	307	0.06	own stratum
275 Sri Lanka montane rain forests	1,500–2,000	63	11.7	15.6	19.6	368	0.07	own stratum
275 Sri Lanka montane rain forests	2,000–2,500	9	6.8	9.3	10.7	78	0.01	fallback
287 Upper Gangetic Plains moist deciduous forests	0–500	811	7.6	11.7	23.8	2,510	0.45	own stratum
287 Upper Gangetic Plains moist deciduous forests	500–1,000	345	21.1	23.7	26.6	1,527	0.27	own stratum
287 Upper Gangetic Plains moist deciduous forests	1,000–1,500	8	21.8	22.8	25.3	381	0.07	fallback
287 Upper Gangetic Plains moist deciduous forests	1,500–2,000	6	22.5	24.3	25.0	173	0.03	fallback
287 Upper Gangetic Plains moist deciduous forests	2,000–2,500	4	19.6	25.2	27.7	36	0.01	fallback
Tropical and subtropical dry broadleaf forests (biome 2)								
290 Central Deccan Plateau dry deciduous forests	0–500	4,034	8.2	12.4	15.3	13,882	2.49	own stratum
290 Central Deccan Plateau dry deciduous forests	500–1,000	2,010	8.5	11.1	13.3	3,997	0.72	own stratum
292 Chhota-Nagpur dry deciduous forests	0–500	1,252	10.5	13.2	15.7	10,776	1.93	own stratum
292 Chhota-Nagpur dry deciduous forests	500–1,000	3,013	13.5	15.9	17.7	7,058	1.27	own stratum
292 Chhota-Nagpur dry deciduous forests	1,000–1,500	33	15.4	19.6	22.6	72	0.01	own stratum
293 East Deccan dry-evergreen forests	0–500	75	4.9	7.3	10.6	343	0.06	own stratum
293 East Deccan dry-evergreen forests	500–1,000	34	7.5	8.2	10.0	45	0.01	own stratum

Ecoregion[a]	Elevation band (m)	Reference cells with height	P5 (m)	P25 (m)	Median (m)	Forest area (km²)	Forest area (% of all forest)	Benchmark source[b]
295 Khathiar-Gir dry deciduous forests	0–500	2,100	5.6	7.5	9.0	5,098	0.91	own stratum
295 Khathiar-Gir dry deciduous forests	500–1,000	308	8.5	10.9	13.2	1,685	0.30	own stratum
295 Khathiar-Gir dry deciduous forests	1,000–1,500	0	–	–	–	60	0.01	fallback
296 Narmada Valley dry deciduous forests	0–500	861	10.9	14.6	17.1	7,020	1.26	own stratum
296 Narmada Valley dry deciduous forests	500–1,000	2,484	12.3	15.6	17.9	5,560	1.00	own stratum
296 Narmada Valley dry deciduous forests	1,000–1,500	12	11.8	14.2	15.9	23	0.00	fallback
297 North Deccan dry deciduous forests	0–500	1,913	11.8	16.4	19.1	8,689	1.56	own stratum
297 North Deccan dry deciduous forests	500–1,000	1,182	10.5	13.3	17.3	3,297	0.59	own stratum
297 North Deccan dry deciduous forests	1,000–1,500	1	14.7	14.7	14.7	2	0.00	fallback
298 South Deccan Plateau dry deciduous forests	0–500	603	7.7	9.5	11.0	2,393	0.43	own stratum
298 South Deccan Plateau dry deciduous forests	500–1,000	1,519	7.6	10.0	12.5	5,807	1.04	own stratum
298 South Deccan Plateau dry deciduous forests	1,000–1,500	310	11.2	14.6	17.3	956	0.17	own stratum
298 South Deccan Plateau dry deciduous forests	1,500–2,000	2	17.8	20.2	23.1	26	0.00	fallback
301 Sri Lanka dry-zone dry evergreen forests	0–500	4,905	6.3	9.1	11.4	15,383	2.76	own stratum
301 Sri Lanka dry-zone dry evergreen forests	500–1,000	6	15.2	20.7	23.1	241	0.04	fallback
Tropical and subtropical coniferous forests (biome 3)								
302 Himalayan subtropical pine forests	0–500	71	19.3	25.3	28.0	618	0.11	own stratum
302 Himalayan subtropical pine forests	500–1,000	841	22.4	26.4	28.7	7,597	1.36	own stratum
302 Himalayan subtropical pine forests	1,000–1,500	1,171	19.8	23.8	26.7	11,208	2.01	own stratum
302 Himalayan subtropical pine forests	1,500–2,000	1,238	19.1	24.1	27.5	8,195	1.47	own stratum
302 Himalayan subtropical pine forests	2,000–2,500	1,149	18.9	23.9	27.2	3,599	0.65	own stratum
302 Himalayan subtropical pine forests	2,500–3,000	504	21.9	28.1	31.8	830	0.15	own stratum
302 Himalayan subtropical pine forests	3,000–3,500	94	21.2	26.2	28.6	109	0.02	own stratum
304 Northeast India-Myanmar pine forests	0–500	6	19.2	20.9	24.4	197	0.04	fallback
304 Northeast India-Myanmar pine forests	500–1,000	38	18.5	20.6	25.3	1,606	0.29	own stratum
304 Northeast India-Myanmar pine forests	1,000–1,500	174	19.2	22.0	24.4	3,286	0.59	own stratum
304 Northeast India-Myanmar pine forests	1,500–2,000	206	23.4	27.6	31.2	2,251	0.40	own stratum
304 Northeast India-Myanmar pine forests	2,000–2,500	324	26.5	29.8	32.3	773	0.14	own stratum
304 Northeast India-Myanmar pine forests	2,500–3,000	112	21.6	24.9	27.2	114	0.02	own stratum
304 Northeast India-Myanmar pine forests	3,000–3,500	17	12.5	16.3	23.3	15	0.00	fallback
Temperate broadleaf and mixed forests (biome 4)								
306 Eastern Himalayan broadleaf forests	0–500	58	22.2	26.4	29.4	4,743	0.85	own stratum
306 Eastern Himalayan broadleaf forests	500–1,000	1,150	24.8	29.3	32.2	11,079	1.99	own stratum
306 Eastern Himalayan broadleaf forests	1,000–1,500	3,306	26.2	30.4	33.2	14,913	2.67	own stratum
306 Eastern Himalayan broadleaf forests	1,500–2,000	4,620	26.5	30.6	33.3	15,312	2.75	own stratum
306 Eastern Himalayan broadleaf forests	2,000–2,500	4,312	25.9	29.8	32.5	12,248	2.20	own stratum
306 Eastern Himalayan broadleaf forests	2,500–3,000	2,923	22.5	27.0	30.6	7,548	1.35	own stratum
306 Eastern Himalayan broadleaf forests	3,000–3,500	947	18.4	24.2	28.7	2,061	0.37	own stratum
306 Eastern Himalayan broadleaf forests	3,500–4,000	81	17.1	22.0	26.6	207	0.04	own stratum
306 Eastern Himalayan broadleaf forests	4,000–4,500	1	15.0	15.0	15.0	2	0.00	fallback
307 Northern Triangle temperate forests	2,000–2,500	1	29.4	29.4	29.4	4	0.00	fallback
308 Western Himalayan broadleaf forests	0–500	0	–	–	–	248	0.04	fallback
308 Western Himalayan broadleaf forests	500–1,000	0	–	–	–	1,206	0.22	fallback

Ecoregion[a]	Elevation band (m)	Reference cells with height	P5 (m)	P25 (m)	Median (m)	Forest area (km²)	Forest area (% of all forest)	Benchmark source[b]
308 Western Himalayan broadleaf forests	1,000–1,500	27	22.3	30.2	32.4	1,536	0.28	fallback
308 Western Himalayan broadleaf forests	1,500–2,000	263	22.6	27.5	30.2	3,569	0.64	own stratum
308 Western Himalayan broadleaf forests	2,000–2,500	1,497	21.0	25.9	29.4	6,084	1.09	own stratum
308 Western Himalayan broadleaf forests	2,500–3,000	2,827	21.7	27.5	31.6	5,956	1.07	own stratum
308 Western Himalayan broadleaf forests	3,000–3,500	1,330	18.5	25.2	28.7	2,082	0.37	own stratum
308 Western Himalayan broadleaf forests	3,500–4,000	16	13.4	17.8	20.2	15	0.00	fallback
Temperate conifer forests (biome 5)								
309 Eastern Himalayan subalpine conifer forests	500–1,000	0	–	–	–	38	0.01	fallback
309 Eastern Himalayan subalpine conifer forests	1,000–1,500	90	26.8	29.4	32.9	425	0.08	own stratum
309 Eastern Himalayan subalpine conifer forests	1,500–2,000	365	27.1	30.8	34.0	1,243	0.22	own stratum
309 Eastern Himalayan subalpine conifer forests	2,000–2,500	1,057	25.5	30.4	33.7	2,996	0.54	own stratum
309 Eastern Himalayan subalpine conifer forests	2,500–3,000	2,248	22.5	27.3	32.2	5,741	1.03	own stratum
309 Eastern Himalayan subalpine conifer forests	3,000–3,500	2,588	19.9	25.8	30.6	6,455	1.16	own stratum
309 Eastern Himalayan subalpine conifer forests	3,500–4,000	1,323	17.1	24.2	29.2	3,082	0.55	own stratum
309 Eastern Himalayan subalpine conifer forests	4,000–4,500	96	9.2	12.8	16.9	258	0.05	own stratum
310 Western Himalayan subalpine conifer forests	0–500	0	–	–	–	109	0.02	fallback
310 Western Himalayan subalpine conifer forests	500–1,000	0	–	–	–	225	0.04	fallback
310 Western Himalayan subalpine conifer forests	1,000–1,500	0	–	–	–	164	0.03	fallback
310 Western Himalayan subalpine conifer forests	1,500–2,000	2	33.6	33.9	34.3	577	0.10	fallback
310 Western Himalayan subalpine conifer forests	2,000–2,500	414	20.8	25.2	28.3	2,927	0.52	own stratum
310 Western Himalayan subalpine conifer forests	2,500–3,000	1,619	22.0	27.0	30.1	4,171	0.75	own stratum
310 Western Himalayan subalpine conifer forests	3,000–3,500	1,626	21.1	25.8	29.5	2,759	0.49	own stratum
310 Western Himalayan subalpine conifer forests	3,500–4,000	83	20.8	24.6	27.8	104	0.02	own stratum
702 Northeast Himalayan subalpine conifer forests	0–500	0	–	–	–	3	0.00	fallback
702 Northeast Himalayan subalpine conifer forests	500–1,000	4	30.9	33.5	35.3	113	0.02	fallback
702 Northeast Himalayan subalpine conifer forests	1,000–1,500	24	26.7	31.3	34.8	86	0.02	fallback
702 Northeast Himalayan subalpine conifer forests	1,500–2,000	61	26.8	30.1	34.1	104	0.02	own stratum
702 Northeast Himalayan subalpine conifer forests	2,000–2,500	176	24.6	29.5	32.0	411	0.07	own stratum
702 Northeast Himalayan subalpine conifer forests	2,500–3,000	226	22.2	28.0	30.8	730	0.13	own stratum
702 Northeast Himalayan subalpine conifer forests	3,000–3,500	249	19.0	25.8	30.4	932	0.17	own stratum
702 Northeast Himalayan subalpine conifer forests	3,500–4,000	118	11.6	17.6	23.2	606	0.11	own stratum
702 Northeast Himalayan subalpine conifer forests	4,000–4,500	1	12.7	12.7	12.7	49	0.01	fallback
Tropical and subtropical grasslands, savannas and shrublands (biome 7)								
311 Terai-Duar savanna and grasslands	0–500	1,677	19.0	23.4	26.5	6,563	1.18	own stratum
311 Terai-Duar savanna and grasslands	500–1,000	148	21.9	25.8	28.6	291	0.05	own stratum
311 Terai-Duar savanna and grasslands	1,000–1,500	15	27.4	30.4	32.3	23	0.00	fallback
Montane grasslands and shrublands (biome 10)								
751 Eastern Himalayan alpine shrub and meadows	1,000–1,500	30	25.0	29.2	34.6	135	0.02	own stratum
751 Eastern Himalayan alpine shrub and meadows	1,500–2,000	167	23.1	29.4	33.8	496	0.09	own stratum
751 Eastern Himalayan alpine shrub and meadows	2,000–2,500	351	26.1	30.4	33.7	992	0.18	own stratum
751 Eastern Himalayan alpine shrub and meadows	2,500–3,000	460	22.8	28.7	33.5	1,516	0.27	own stratum
751 Eastern Himalayan alpine shrub and meadows	3,000–3,500	583	18.3	24.3	28.7	2,188	0.39	own stratum
751 Eastern Himalayan alpine shrub and meadows	3,500–4,000	192	11.6	19.6	24.2	1,547	0.28	own stratum

Ecoregion[a]	Elevation band (m)	Reference cells with height	P5 (m)	P25 (m)	Median (m)	Forest area (km²)	Forest area (% of all forest)	Benchmark source[b]
751 Eastern Himalayan alpine shrub and meadows	4,000–4,500	53	8.3	11.3	15.7	306	0.05	own stratum
754 Karakoram-West Tibetan Plateau alpine steppe	2,500–3,000	1	9.3	9.3	9.3	3	0.00	fallback
754 Karakoram-West Tibetan Plateau alpine steppe	3,000–3,500	16	17.0	19.8	21.7	42	0.01	fallback
754 Karakoram-West Tibetan Plateau alpine steppe	3,500–4,000	3	10.9	12.9	15.4	6	0.00	fallback
760 Northwestern Himalayan alpine shrub and meadows	1,500–2,000	18	15.3	19.5	21.8	72	0.01	fallback
760 Northwestern Himalayan alpine shrub and meadows	2,000–2,500	185	16.3	21.5	25.8	569	0.10	own stratum
760 Northwestern Himalayan alpine shrub and meadows	2,500–3,000	670	17.1	23.5	28.3	1,534	0.27	own stratum
760 Northwestern Himalayan alpine shrub and meadows	3,000–3,500	284	19.4	23.5	26.8	666	0.12	own stratum
760 Northwestern Himalayan alpine shrub and meadows	3,500–4,000	3	18.0	18.6	19.5	8	0.00	fallback
766 Sulaiman Range alpine meadows	500–1,000	0	–	–	–	2	0.00	fallback
766 Sulaiman Range alpine meadows	1,000–1,500	22	7.9	8.8	11.0	46	0.01	fallback
766 Sulaiman Range alpine meadows	1,500–2,000	63	8.8	11.1	13.3	200	0.04	own stratum
766 Sulaiman Range alpine meadows	2,000–2,500	269	8.7	12.4	15.7	528	0.09	own stratum
766 Sulaiman Range alpine meadows	2,500–3,000	251	9.3	12.5	16.8	382	0.07	own stratum
766 Sulaiman Range alpine meadows	3,000–3,500	48	12.2	16.9	20.9	62	0.01	own stratum
769 Western Himalayan alpine shrub and meadows	1,500–2,000	0	–	–	–	5	0.00	fallback
769 Western Himalayan alpine shrub and meadows	2,000–2,500	0	–	–	–	87	0.02	fallback
769 Western Himalayan alpine shrub and meadows	2,500–3,000	4	27.9	30.3	32.1	424	0.08	fallback
769 Western Himalayan alpine shrub and meadows	3,000–3,500	405	20.4	25.1	28.9	1,095	0.20	own stratum
769 Western Himalayan alpine shrub and meadows	3,500–4,000	287	18.1	23.1	26.6	487	0.09	own stratum
Deserts and xeric shrublands (biome 13)								
314 Aravalli west thorn scrub forests	0–500	164	6.6	8.8	13.1	978	0.18	own stratum
314 Aravalli west thorn scrub forests	500–1,000	208	11.5	14.9	19.2	1,711	0.31	own stratum
314 Aravalli west thorn scrub forests	1,000–1,500	32	12.6	15.2	19.1	372	0.07	own stratum
314 Aravalli west thorn scrub forests	1,500–2,000	9	16.0	22.2	22.9	94	0.02	fallback
314 Aravalli west thorn scrub forests	2,000–2,500	12	19.7	22.0	23.9	45	0.01	fallback
314 Aravalli west thorn scrub forests	2,500–3,000	6	26.1	29.4	33.3	15	0.00	fallback
314 Aravalli west thorn scrub forests	3,000–3,500	1	25.4	25.4	25.4	2	0.00	fallback
315 Deccan thorn scrub forests	0–500	787	4.9	8.0	10.0	2,382	0.43	own stratum
315 Deccan thorn scrub forests	500–1,000	564	7.5	8.9	10.3	1,915	0.34	own stratum
315 Deccan thorn scrub forests	1,000–1,500	6	12.1	12.7	14.0	42	0.01	fallback
316 Godavari-Krishna mangroves	0–500	13	4.0	4.2	4.5	135	0.02	fallback
318 Thar desert	0–500	0	–	–	–	8	0.00	fallback
814 Baluchistan xeric woodlands	0–500	2	8.5	8.8	9.1	192	0.03	fallback
814 Baluchistan xeric woodlands	500–1,000	21	5.6	6.5	8.2	516	0.09	fallback
814 Baluchistan xeric woodlands	1,000–1,500	77	6.5	9.1	10.9	325	0.06	own stratum
814 Baluchistan xeric woodlands	1,500–2,000	109	7.7	10.1	12.3	221	0.04	own stratum
814 Baluchistan xeric woodlands	2,000–2,500	63	7.8	11.4	13.7	81	0.01	own stratum
814 Baluchistan xeric woodlands	2,500–3,000	28	8.3	10.1	13.4	30	0.01	fallback
Mangroves (biome 14)								
321 Myanmar Coast mangroves	0–500	3	11.6	11.9	12.2	19	0.00	fallback
323 Sundarbans mangroves	0–500	2,499	4.2	5.0	7.0	4,731	0.85	own stratum
No ecoregion (biome 99)								

Ecoregion[a]	Elevation band (m)	Reference cells with height	P5 (m)	P25 (m)	Median (m)	Forest area (km²)	Forest area (% of all forest)	Benchmark source[b]
999 No RESOLVE ecoregion (coastal edge cells)	0–500	131	17.2	26.7	30.8	558	0.10	own stratum

[a] RESOLVE Ecoregions 2017: ECO_ID and name; 999 marks coastal cells outside the ecoregion polygons. [b] Strata with < 30 reference cells take the benchmark of the first level with ≥ 30: the whole ecoregion, then biome × elevation band, then biome. Strata with < 1 km² of forest are not listed.

Table S4. Level 2 classes by country (km²), related to Figure 3. Area of each class of Figure 3a; structural states relative to reference-forest benchmarks (Table S3).

Class	India	Pakistan	Nepal	Bhutan	Bangladesh	Sri Lanka	South Asia
Greening, reference-like forest	96,888	2,580	7,195	1,363	2,496	3,754	114,276
Greening, moderately depleted forest	58,758	1,675	7,060	1,055	718	1,244	70,510
Greening, strongly depleted forest	42,610	2,622	6,284	1,400	598	312	53,825
No majority trend, reference-like forest	103,116	2,372	13,483	15,058	6,875	8,006	148,910
No majority trend, moderately depleted forest	43,674	1,080	6,836	4,493	1,427	1,954	59,464
No majority trend, strongly depleted forest	31,485	749	3,703	2,160	1,975	500	40,573
Forest, structure not assessed	109,008	8,980	15,125	3,000	1,986	5,836	143,934
Browning forest (any state)	3,216	149	683	359	458	144	5,009
Other woody vegetation or no MODIS trend	136,622	96,363	13,596	2,940	6,888	19,774	276,184
Total	**625,377**	**116,570**	**73,965**	**31,828**	**23,421**	**41,524**	**912,685**

Table S5. Greening shares, gaps and depleted-area estimates under alternative analysis choices, with 95% confidence intervals, related to Figures 3 and 4c.

Specification	Greening, reference-like (%)	Greening, moderately depleted (%)	Greening, strongly depleted (%)	Gap, pooled (points; 95% CI)	Gap within strata (points; 95% CI)	Depleted forest, % (expected)	Excess depleted (points)	Strata	Strata with positive gap (%)	Replicates
Primary analysis										
Primary analysis	43.1 (37.6 to 48.4)	53.8 (48.6 to 58.1)	56.1 (51.3 to 61.8)	13.0 (7.8 to 19.0)	16.6 (13.0 to 19.3)	46.1 (25)	21.1 (18.1 to 24.7)	116	87	1,000
Canopy height data										
Leaf-on shots only	34.2 (29.7 to 38.9)	45.2 (40.5 to 48.9)	51.6 (47.6 to 57.0)	17.5 (12.7 to 22.3)	17.1 (14.0 to 20.0)	45.9 (25)	20.9	111	86	300
Gridded GEDI product (leaf-on)	36.5 (31.9 to 41.5)	46.9 (42.3 to 51.7)	52.2 (47.5 to 58.6)	15.7 (11.1 to 20.8)	14.1 (11.6 to 16.6)	46.1 (25)	21.1	111	85	300
Leaf-off bias removed	43.1 (37.4 to 48.1)	53.7 (48.5 to 57.4)	56.1 (51.5 to 61.0)	13.0 (7.6 to 18.7)	16.5 (13.0 to 19.1)	46.0 (25)	21.0	116	86	300
State thresholds										
Benchmarks P2.5 / P15	44.7 (39.1 to 50.3)	55.3 (50.5 to 60.2)	56.0 (50.8 to 62.7)	11.4 (6.1 to 18.1)	15.8 (12.9 to 18.8)	34.7 (15)	19.7	104	88	300
Benchmarks P10 / P33	41.9 (37.2 to 47.5)	52.2 (46.8 to 56.5)	55.9 (51.7 to 61.2)	14.0 (7.8 to 18.8)	16.4 (13.1 to 18.9)	53.7 (33)	20.7	126	85	300
Reference forest										
Reference: lowest quarter of pressure	43.0 (37.4 to 48.8)	53.2 (48.0 to 57.5)	56.2 (51.7 to 61.5)	13.1 (7.8 to 19.6)	16.6 (13.0 to 18.9)	47.2 (25)	22.2	117	87	300
Reference: lowest half of pressure	43.7 (38.7 to 49.1)	54.4 (49.7 to 59.4)	54.9 (49.8 to 60.8)	11.3 (5.8 to 17.6)	16.8 (13.2 to 19.2)	43.9 (25)	18.9	116	86	300
Forest definition										
Forest share ≥ 0.6	43.1 (38.1 to 47.9)	53.9 (49.1 to 58.0)	57.0 (52.5 to 61.9)	13.8 (8.5 to 19.4)	16.6 (13.5 to 19.2)	48.2 (25)	23.2	125	86	300
Forest share ≥ 0.8	43.0 (37.4 to 48.6)	53.3 (48.8 to 58.0)	54.7 (50.1 to 60.3)	11.8 (6.0 to 18.3)	16.4 (12.6 to 19.4)	43.4 (25)	18.4	103	89	300
Forest share ≥ 0.9	42.4 (36.3 to 47.9)	51.9 (46.4 to 57.3)	53.2 (48.9 to 58.9)	10.8 (4.8 to 16.7)	16.2 (12.8 to 18.6)	39.2 (25)	14.2	93	86	300
No planted forest (JRC map)	42.6 (37.6 to 48.9)	53.2 (48.8 to 58.6)	55.5 (50.6 to 62.2)	13.0 (8.5 to 18.7)	16.7 (13.6 to 19.4)	45.9 (25)	20.9	115	86	300
Terrain										
Slope-matched benchmarks	42.5 (37.5 to 47.8)	53.8 (48.4 to 58.3)	57.0 (52.0 to 63.0)	14.5 (9.4 to 19.9)	16.9 (13.4 to 19.0)	46.8 (25)	21.8	242	85	300
Gentle terrain only (slope < 15°)	59.2 (54.0 to 65.1)	67.6 (62.0 to 72.4)	62.6 (56.8 to 70.3)	3.4 (−3.4 to 11.4)	12.0 (6.4 to 16.4)	41.4 (25)	16.4	54	85	300
Cropland										
No cropland (Copernicus)	39.5 (33.7 to 45.4)	48.8 (43.7 to 53.5)	50.4 (46.2 to 56.3)	10.9 (5.8 to 17.2)	16.6 (13.0 to 19.8)	42.8 (25)	17.8	107	84	300
No cropland (WorldCover)	38.5 (33.1 to 43.9)	46.7 (42.0 to 51.7)	51.5 (47.0 to 56.8)	13.0 (8.4 to 17.5)	16.9 (13.6 to 19.4)	37.1 (25)	12.1	106	85	300
Saturation										
Least green fifth (baseline NDVI)	73.4 (67.6 to 78.2)	75.5 (71.4 to 79.6)	80.0 (75.8 to 83.8)	6.6 (1.9 to 12.5)	4.2 (1.3 to 8.0)	57.8 (25)	32.8	57	67	300
Greenest fifth (baseline NDVI)	13.1 (7.4 to 19.2)	24.4 (14.7 to 33.7)	26.6 (17.7 to 36.1)	13.5 (9.1 to 18.8)	7.2 (4.9 to 9.6)	37.7 (25)	12.7	30	90	300
Least green fifth (baseline EVI)	35.9 (29.8 to 44.0)	53.0 (46.0 to 59.8)	69.4 (62.4 to 75.9)	33.4 (25.3 to 39.9)	12.1 (9.2 to 14.8)	42.9 (25)	17.9	58	78	300

Specification	Greening, reference-like (%)	Greening, moderately depleted (%)	Greening, strongly depleted (%)	Gap, pooled (points; 95% CI)	Gap within strata (points; 95% CI)	Depleted forest, % (expected)	Excess depleted (points)	Strata	Strata with positive gap (%)	Replicates
Greenest fifth (baseline EVI)	29.3 (22.0 to 35.5)	39.6 (30.4 to 45.8)	37.5 (31.9 to 43.4)	8.2 (4.2 to 15.8)	5.7 (0.8 to 12.3)	55.6 (25)	30.6	33	85	300
Greening rule and period										
Greening if ≥ 25% of pixels	56.7 (50.7 to 62.2)	67.8 (63.9 to 72.1)	70.7 (66.8 to 75.5)	14.1 (9.1 to 19.6)	15.5 (11.8 to 17.9)	46.1 (25)	21.1	116	83	300
Greening if ≥ 75% of pixels	30.9 (26.4 to 35.7)	39.1 (34.6 to 43.3)	40.9 (36.1 to 46.3)	9.9 (4.4 to 16.1)	14.8 (11.4 to 17.3)	46.1 (25)	21.1	116	85	300
Continuous greening share	42.9 (38.1 to 47.8)	52.1 (47.8 to 55.8)	54.4 (50.0 to 58.6)	11.5 (7.0 to 16.3)	14.7 (11.7 to 16.8)	46.1 (25)	21.1	116	86	300
≥ 90% of cell valid natural forest	43.0 (36.8 to 48.9)	53.2 (48.2 to 58.6)	54.5 (49.5 to 60.5)	11.6 (6.6 to 17.7)	16.3 (12.4 to 18.8)	42.6 (25)	17.6	100	87	300
Greening over 2001–2019	22.2 (19.1 to 25.6)	31.5 (27.6 to 34.7)	37.9 (33.5 to 43.4)	15.8 (11.2 to 20.6)	15.1 (11.3 to 17.8)	46.1 (25)	21.1	116	82	300

Table S6. Within-stratum greening gaps by ecoregion and elevation band, related to Figure 4b. Gap in each of the 116 strata with at least 20 cells of both reference-like and strongly depleted natural forest.

Ecoregion	Elevation band (m)	Assessed natural forest (km²)	Gap (points)
Tropical and subtropical moist broadleaf forests: 41 strata; area-weighted mean 19.1 points			
218 Andaman Islands rain forests	0–500	4,061	10.1
222 Brahmaputra Valley semi-evergreen forests	0–500	6,080	19.7
222 Brahmaputra Valley semi-evergreen forests	500–1,000	660	7.1
222 Brahmaputra Valley semi-evergreen forests	1,000–1,500	79	21.9
228 East Deccan moist deciduous forests	0–500	45,630	14.5
228 East Deccan moist deciduous forests	500–1,000	35,246	17.6
228 East Deccan moist deciduous forests	1,000–1,500	835	16.1
233 Himalayan subtropical broadleaf forests	0–500	6,428	30.1
233 Himalayan subtropical broadleaf forests	500–1,000	9,782	35.0
233 Himalayan subtropical broadleaf forests	1,000–1,500	1,074	26.1
233 Himalayan subtropical broadleaf forests	2,500–3,000	126	12.9
233 Himalayan subtropical broadleaf forests	3,000–3,500	232	7.9
238 Lower Gangetic Plains moist deciduous forests	0–500	9,254	24.7
242 Malabar Coast moist forests	0–500	2,565	32.5
244 Meghalaya subtropical forests	0–500	14,141	14.3
244 Meghalaya subtropical forests	500–1,000	7,966	16.9
244 Meghalaya subtropical forests	1,000–1,500	1,867	24.9
244 Meghalaya subtropical forests	1,500–2,000	211	33.9
249 Mizoram-Manipur-Kachin rain forests	0–500	23,336	−13.8
249 Mizoram-Manipur-Kachin rain forests	500–1,000	17,718	10.4
249 Mizoram-Manipur-Kachin rain forests	1,000–1,500	9,216	29.2
249 Mizoram-Manipur-Kachin rain forests	1,500–2,000	1,936	22.3
249 Mizoram-Manipur-Kachin rain forests	2,000–2,500	412	10.0
252 Nicobar Islands rain forests	0–500	833	5.2
253 North Western Ghats moist deciduous forests	0–500	5,342	60.3
253 North Western Ghats moist deciduous forests	500–1,000	2,408	48.4
254 North Western Ghats montane rain forests	0–500	4,123	48.7
254 North Western Ghats montane rain forests	500–1,000	6,222	53.1
254 North Western Ghats montane rain forests	1,000–1,500	734	48.8
261 Orissa semi-evergreen forests	0–500	1,553	1.8
270 South Western Ghats moist deciduous forests	0–500	1,409	77.6
270 South Western Ghats moist deciduous forests	500–1,000	3,285	36.7
270 South Western Ghats moist deciduous forests	1,000–1,500	1,078	37.8
271 South Western Ghats montane rain forests	0–500	1,908	47.9
271 South Western Ghats montane rain forests	500–1,000	3,478	42.7
271 South Western Ghats montane rain forests	1,000–1,500	2,045	20.2
271 South Western Ghats montane rain forests	1,500–2,000	381	22.9
274 Sri Lanka lowland rain forests	0–500	681	50.9
274 Sri Lanka lowland rain forests	500–1,000	535	41.7
287 Upper Gangetic Plains moist deciduous forests	0–500	1,786	11.9
287 Upper Gangetic Plains moist deciduous forests	500–1,000	1,400	−11.8
Tropical and subtropical dry broadleaf forests: 15 strata; area-weighted mean 1.5 points			

Ecoregion	Elevation band (m)	Assessed natural forest (km²)	Gap (points)
290 Central Deccan Plateau dry deciduous forests	0–500	12,121	1.4
290 Central Deccan Plateau dry deciduous forests	500–1,000	3,247	−6.9
292 Chhota-Nagpur dry deciduous forests	0–500	9,194	−17.3
292 Chhota-Nagpur dry deciduous forests	500–1,000	6,472	−16.8
293 East Deccan dry-evergreen forests	0–500	255	3.5
295 Khathiar-Gir dry deciduous forests	0–500	4,185	5.8
295 Khathiar-Gir dry deciduous forests	500–1,000	1,260	−0.5
296 Narmada Valley dry deciduous forests	0–500	5,651	0.8
296 Narmada Valley dry deciduous forests	500–1,000	4,715	−8.6
297 North Deccan dry deciduous forests	0–500	8,197	17.5
297 North Deccan dry deciduous forests	500–1,000	3,110	24.0
298 South Deccan Plateau dry deciduous forests	0–500	1,740	20.6
298 South Deccan Plateau dry deciduous forests	500–1,000	4,533	13.5
298 South Deccan Plateau dry deciduous forests	1,000–1,500	652	15.6
301 Sri Lanka dry-zone dry evergreen forests	0–500	13,548	5.6
Tropical and subtropical coniferous forests: 11 strata; area-weighted mean 27.1 points			
302 Himalayan subtropical pine forests	0–500	457	9.8
302 Himalayan subtropical pine forests	500–1,000	7,111	31.0
302 Himalayan subtropical pine forests	1,000–1,500	10,666	26.9
302 Himalayan subtropical pine forests	1,500–2,000	7,907	29.8
302 Himalayan subtropical pine forests	2,000–2,500	3,504	30.2
302 Himalayan subtropical pine forests	2,500–3,000	799	22.0
304 Northeast India-Myanmar pine forests	0–500	196	30.9
304 Northeast India-Myanmar pine forests	500–1,000	1,554	7.5
304 Northeast India-Myanmar pine forests	1,000–1,500	3,231	17.5
304 Northeast India-Myanmar pine forests	1,500–2,000	2,232	32.1
304 Northeast India-Myanmar pine forests	2,000–2,500	764	30.4
Temperate broadleaf and mixed forests: 13 strata; area-weighted mean 25.6 points			
306 Eastern Himalayan broadleaf forests	0–500	4,234	12.9
306 Eastern Himalayan broadleaf forests	500–1,000	9,073	13.4
306 Eastern Himalayan broadleaf forests	1,000–1,500	12,040	29.9
306 Eastern Himalayan broadleaf forests	1,500–2,000	12,235	40.1
306 Eastern Himalayan broadleaf forests	2,000–2,500	10,004	42.0
306 Eastern Himalayan broadleaf forests	2,500–3,000	6,224	23.0
306 Eastern Himalayan broadleaf forests	3,000–3,500	1,728	6.4
308 Western Himalayan broadleaf forests	500–1,000	1,116	15.9
308 Western Himalayan broadleaf forests	1,000–1,500	1,426	27.1
308 Western Himalayan broadleaf forests	1,500–2,000	3,368	28.6
308 Western Himalayan broadleaf forests	2,000–2,500	5,848	22.8
308 Western Himalayan broadleaf forests	2,500–3,000	5,698	5.7
308 Western Himalayan broadleaf forests	3,000–3,500	1,950	−2.5
Temperate conifer forests: 13 strata; area-weighted mean 14.8 points			
309 Eastern Himalayan subalpine conifer forests	1,000–1,500	256	39.6
309 Eastern Himalayan subalpine conifer forests	1,500–2,000	798	40.5

Ecoregion	Elevation band (m)	Assessed natural forest (km²)	Gap (points)
309 Eastern Himalayan subalpine conifer forests	2,000–2,500	2,186	32.3
309 Eastern Himalayan subalpine conifer forests	2,500–3,000	4,587	13.7
309 Eastern Himalayan subalpine conifer forests	3,000–3,500	5,537	7.8
309 Eastern Himalayan subalpine conifer forests	3,500–4,000	2,661	2.6
309 Eastern Himalayan subalpine conifer forests	4,000–4,500	224	9.0
310 Western Himalayan subalpine conifer forests	1,500–2,000	531	10.4
310 Western Himalayan subalpine conifer forests	2,000–2,500	2,789	25.3
310 Western Himalayan subalpine conifer forests	2,500–3,000	3,892	11.9
310 Western Himalayan subalpine conifer forests	3,000–3,500	2,569	11.9
702 Northeast Himalayan subalpine conifer forests	2,500–3,000	329	26.3
702 Northeast Himalayan subalpine conifer forests	3,000–3,500	540	15.0
Tropical and subtropical grasslands, savannas and shrublands: 2 strata; area-weighted mean 10.5 points			
311 Terai-Duar savanna and grasslands	0–500	5,082	9.8
311 Terai-Duar savanna and grasslands	500–1,000	282	22.5
Montane grasslands and shrublands: 13 strata; area-weighted mean 3.4 points			
751 Eastern Himalayan alpine shrub and meadows	1,000–1,500	68	5.0
751 Eastern Himalayan alpine shrub and meadows	1,500–2,000	309	16.8
751 Eastern Himalayan alpine shrub and meadows	2,000–2,500	592	11.4
751 Eastern Himalayan alpine shrub and meadows	2,500–3,000	889	1.1
751 Eastern Himalayan alpine shrub and meadows	3,000–3,500	1,435	2.4
751 Eastern Himalayan alpine shrub and meadows	3,500–4,000	1,082	1.1
760 Northwestern Himalayan alpine shrub and meadows	2,000–2,500	508	−21.0
760 Northwestern Himalayan alpine shrub and meadows	2,500–3,000	1,399	1.1
760 Northwestern Himalayan alpine shrub and meadows	3,000–3,500	596	1.4
766 Sulaiman Range alpine meadows	2,000–2,500	490	−10.6
766 Sulaiman Range alpine meadows	2,500–3,000	341	−12.5
769 Western Himalayan alpine shrub and meadows	3,000–3,500	977	25.8
769 Western Himalayan alpine shrub and meadows	3,500–4,000	450	11.9
Deserts and xeric shrublands: 6 strata; area-weighted mean 2.3 points			
314 Aravalli west thorn scrub forests	0–500	889	6.7
314 Aravalli west thorn scrub forests	500–1,000	1,532	−1.9
315 Deccan thorn scrub forests	0–500	1,979	4.7
315 Deccan thorn scrub forests	500–1,000	1,557	2.4
814 Baluchistan xeric woodlands	0–500	131	0.0
814 Baluchistan xeric woodlands	500–1,000	471	−1.3
Mangroves: 1 stratum; area-weighted mean −26.3 points			
323 Sundarbans mangroves	0–500	4,040	−26.3
No ecoregion: 1 stratum; area-weighted mean 38.9 points			
999 No RESOLVE ecoregion (coastal edge cells)	0–500	484	38.9
All strata		**482,777**	**16.6**

Table S7. Disturbance history by structural state and greening trajectory: within-stratum contrasts with 95% confidence intervals, related to Figure 5. Differences between groups of moist natural forest in the Landsat-based JRC Tropical Moist Forest record, estimated within ecoregion × 500 m elevation-band strata with at least 20 cells of each group and averaged with area weights, and pooled over all cells.

Contrast	Metric	Subset	Within strata (95% CI)	Strata	Strata with positive difference (%)	Pooled (95% CI)
A. Structural state: depleted minus reference-like forest						
Strongly depleted minus reference-like	Undisturbed since 1990 (% of cell)	moist forest (TMF)	−21.3 (−25.0 to −16.8)	42	2	−24.1 (−27.9 to −20.1)
Moderately depleted minus reference-like	Undisturbed since 1990 (% of cell)	moist forest (TMF)	−11.8 (−13.9 to −9.4)	63	5	−11.4 (−14.3 to −8.6)
Strongly depleted minus reference-like	Disturbed 1990–2000 (% of cell)	moist forest (TMF)	7.7 (5.6 to 9.2)	42	90	9.9 (7.8 to 11.6)
Moderately depleted minus reference-like	Disturbed 1990–2000 (% of cell)	moist forest (TMF)	3.9 (3.2 to 4.7)	63	84	4.1 (3.1 to 5.2)
Strongly depleted minus reference-like	Degraded forest in 2020 (% of cell)	moist forest (TMF)	0.2 (−2.3 to 2.3)	42	50	0.2 (−2.3 to 2.4)
Moderately depleted minus reference-like	Degraded forest in 2020 (% of cell)	moist forest (TMF)	0.5 (−1.0 to 1.8)	63	70	0.0 (−1.6 to 1.5)
Strongly depleted minus reference-like	Regrowing forest in 2020 (% of cell)	moist forest (TMF)	4.7 (3.6 to 5.6)	42	90	5.0 (3.6 to 6.2)
Moderately depleted minus reference-like	Regrowing forest in 2020 (% of cell)	moist forest (TMF)	2.8 (2.4 to 3.2)	63	89	2.7 (2.0 to 3.2)
Strongly depleted minus reference-like	Deforested by 2020 (% of cell)	moist forest (TMF)	9.1 (6.5 to 11.6)	42	93	13.0 (9.3 to 16.8)
Moderately depleted minus reference-like	Deforested by 2020 (% of cell)	moist forest (TMF)	3.8 (2.9 to 4.7)	63	87	4.6 (3.4 to 6.1)
B. Trajectory: greening minus not greening, within each state						
Depleted (moderate + strong): greening minus not greening	Undisturbed since 1990 (% of cell)	moist forest (TMF)	−10.5 (−13.3 to −8.2)	35	6	−14.6 (−18.0 to −10.3)
Strongly depleted: greening minus not greening	Undisturbed since 1990 (% of cell)	moist forest (TMF)	−6.5 (−8.7 to −4.4)	22	9	−9.0 (−11.6 to −5.1)
Reference-like: greening minus not greening	Undisturbed since 1990 (% of cell)	moist forest (TMF)	−18.4 (−20.4 to −15.3)	48	0	−24.0 (−28.0 to −20.3)
Depleted (moderate + strong): greening minus not greening	Disturbed 1990–2000 (% of cell)	moist forest (TMF)	3.9 (2.8 to 5.4)	35	91	5.7 (4.1 to 7.3)
Strongly depleted: greening minus not greening	Disturbed 1990–2000 (% of cell)	moist forest (TMF)	3.4 (2.1 to 4.9)	22	82	4.3 (2.6 to 5.6)
Reference-like: greening minus not greening	Disturbed 1990–2000 (% of cell)	moist forest (TMF)	5.2 (3.9 to 6.2)	48	94	5.8 (3.2 to 8.2)
Depleted (moderate + strong): greening minus not greening	Degraded forest in 2020 (% of cell)	moist forest (TMF)	0.9 (−0.5 to 2.2)	35	57	0.5 (−1.2 to 2.3)
Strongly depleted: greening minus not greening	Degraded forest in 2020 (% of cell)	moist forest (TMF)	0.6 (−0.8 to 1.7)	22	50	0.7 (−0.9 to 2.4)
Reference-like: greening minus not greening	Degraded forest in 2020 (% of cell)	moist forest (TMF)	2.1 (0.1 to 4.1)	48	60	4.9 (0.3 to 10.1)
Depleted (moderate + strong): greening minus not greening	Regrowing forest in 2020 (% of cell)	moist forest (TMF)	7.7 (6.5 to 8.5)	35	100	7.9 (6.5 to 9.0)
Strongly depleted: greening minus not greening	Regrowing forest in 2020 (% of cell)	moist forest (TMF)	7.8 (6.3 to 8.8)	22	95	8.3 (7.1 to 9.3)
Reference-like: greening minus not greening	Regrowing forest in 2020 (% of cell)	moist forest (TMF)	7.0 (5.7 to 8.2)	48	98	6.3 (4.6 to 8.2)
Depleted (moderate + strong): greening minus not greening	Deforested by 2020 (% of cell)	moist forest (TMF)	−2.2 (−3.4 to −0.3)	35	43	0.7 (−2.2 to 3.2)
Strongly depleted: greening minus not greening	Deforested by 2020 (% of cell)	moist forest (TMF)	−4.9 (−6.7 to −2.6)	22	27	−3.8 (−7.8 to −1.0)
Reference-like: greening minus not greening	Deforested by 2020 (% of cell)	moist forest (TMF)	1.8 (0.5 to 2.9)	48	79	4.7 (1.7 to 7.9)

All metrics are restricted to cells with ≥ 50% moist forest in 1990 (Methods). Units: % of cell.

Table S8. Aboveground carbon deficit of natural forest by country, related to Figure 6. Deficit relative to the mean aboveground biomass (GEDI L4A) of reference forest in the same stratum, summed over all assessed natural forest with valid biomass and a MODIS trajectory, so that forest above the reference mean offsets forest below it (carbon fraction 0.47; Methods), split by greening trajectory.

Unit	Deficit in greening forest (Tg C; 95% CI)	Deficit in forest not greening (Tg C)	Total deficit (Tg C; 95% CI)	Deficit as % of stock at reference biomass	Share of deficit in greening forest (%)	Share of area greening (%)	Shortfall of depleted forest (Tg C)	Surplus of reference-like forest (Tg C)
India	262.9 (203.6 to 332.6)	182.6	445.5 (343.1 to 586.7)	15.5	59.0	52.3	549.7	104.2
Pakistan	21.2 (4.5 to 48.5)	6.8	28.0 (7.6 to 56.9)	24.9	75.7	61.7	30.2	2.2
Nepal	55.3 (27.2 to 84.7)	34.4	89.8 (45.3 to 135.8)	17.9	61.6	45.5	97.5	7.7
Bhutan	12.6 (2.6 to 28.3)	10.2	22.8 (4.2 to 50.9)	6.7	55.2	14.8	42.5	19.7
Bangladesh	1.8 (−1.3 to 8.0)	5.7	7.5 (−5.2 to 35.8)	10.2	–	26.4	16.3	8.8
Sri Lanka	−1.2 (−3.3 to 0.7)	−0.9	−2.1 (−5.3 to 1.8)	−4.2	–	33.5	5.4	7.5
South Asia	**352.7 (285.7 to 426.5)**	**238.9**	**591.6 (475.3 to 740.4)**	**15.0 (13.1 to 17.4)**	**59.6 (53.6 to 64.8)**	**48.6 (43.9 to 53.0)**	**741.7**	**150.1**

Negative values mean more carbon than at reference biomass; the share in greening forest is not shown where the 95% CI of the total includes zero. Confidence intervals: 500 spatial block bootstrap replicates with reference biomass, benchmarks and states re-estimated; they do not include the error of the L4A biomass models. Reference forest is least disturbed and itself partly disturbed, so the deficit is conservative. Units are the areas each country administers.