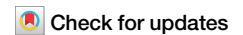


<https://doi.org/10.1038/s43247-026-04035-4>

Land use sequestration potential and uncertainties in India's net-zero pathway

Joy Rajbanshi¹, Vaibhav Chaturvedi^{1,2}✉, Rajiv Kumar Chaturvedi³, Swati Sharma¹ & Raman Sukumar⁴

Land use can contribute substantially to climate change mitigation through carbon storage in vegetation and soils. We assess how India's long-term land-use carbon sequestration may vary under different policy pathways and biophysical uncertainties by integrating economic dynamics with soil and vegetation carbon responses across major land-use classes. Here we show that scientific and policy uncertainties strongly influence India's projected land-use sequestration. Across the full uncertainty range, forests and tree cover could sequester an additional 8.8–31.8 gigatonnes of carbon dioxide equivalent between 2015 and 2070, depending on soil carbon accumulation rates and densities, the timing of achieving the 33% forest and tree cover target (2050 or 2070), and the extent of agroforestry adoption. Annual sequestration across forests, tree cover, croplands, grasslands, shrublands, and fallow lands is projected to range from 68 to 719 million tonnes of carbon dioxide equivalent in 2070. We also find that India is on track to meet its 2030 climate commitment.

The world, in the last couple of decades, has confronted increasing occurrences of hunger, water scarcity, land degradation, extreme weather events, natural calamities and loss of biodiversity^{1–3}. This confirms that climate change is no longer a threat that is supposed to confront us in the future; rather, we are already experiencing its impacts. The Paris Agreement on climate change (2015) has, therefore, focused on limiting global warming to “well below 2 °C, as well as to make efforts to limit the warming to 1.5 °C above pre-industrial levels”. The goal of limiting 1.5 °C warming would require a 43% reduction in greenhouse gas (GHG) emissions by the year 2030 compared to 2019⁴. In this regard, terrestrial carbon sinks have been considered very important by several researchers as they can capture about one-fifth of the emitted carbon from the atmosphere every year^{5,6}. Globally, forests emit about 5.9 GtCO₂ per year as of 2010–2019 (anthropogenic emissions); however, it is estimated that forests and land use sector can sequester about 12.5 GtCO₂ per year, resulting in a net reduction of 6.6 GtCO₂ per year⁷.

In India, the land use, land-use change, and forestry (LULUCF) sector sequestered 15.5% of India's total GHG emissions in 2019⁸, with cropland and forests being the primary contributors to sequestration. Given the varying and sometimes overlapping definitions of forest and tree categories in India, including Forest Cover, Recorded Forest Area, Tree Cover, and Trees Outside Forest (TOF), we use the term Forest and Tree Cover (FTC) throughout this paper as a collective term for all tree-covered areas both within and outside legally designated forests. To increase FTC-driven sequestration, India has pledged to create an additional carbon sink of

2.5–3 GtCO₂eq through promoting the expansion of FTC as well as restoring 26 million hectares (Mha) of deforested and degraded lands by 2030⁸. Besides, the National Forest Policy (1988) of India aims to bring 33% of the total area of the country under FTC from the current levels of about 25%⁹. However, this expansion of FTC must be viewed in tandem with the food security concerns of a nation. With the growing population and urbanization, the country is expected to face a large demand for food in future, resulting in further expansion of the agricultural sector¹⁰ that is bound to impact other land use classes. While Sustainable Development Goal (SDG) 2 (“zero hunger”) demands agricultural development, SDG 13 (“climate action”) and SDG 15 (“life on land”) require protection and expansion of forested areas^{11,12}.

Several studies have looked into the mitigation potential of forests and land use sector in India^{13–15}, the food-land-climate nexus under climate change scenarios^{16,17}, and the role of the energy sector in India and its implications in reaching net zero emissions^{18–20}. In addition, recent integrated assessment studies have explored the role of carbon dioxide removal (CDR) portfolios and land-based removal options in achieving global and regional climate targets. These analyses examine the energy-land-water trade-offs associated with large-scale CDR deployment and its implications for India's net-zero pathway^{21–24}. However, these studies primarily focus on technology portfolios, mitigation costs or energy-system transformations, with limited representation of the dynamic carbon processes within soils and terrestrial ecosystems. As a result, existing assessments for India typically evaluate these components either in isolation or focus on static

¹Council on Energy, Environment and Water, New Delhi, India. ²Adjunct Faculty, Strategic Management Area, XLRI, Jamshedpur, India. ³Birla Institute of Technology and Science, Pilani, K. K. Birla Goa Campus, Zuari Nagar, Goa, India. ⁴Centre for Ecological Sciences, Indian Institute of Science, Bangalore, India.

✉ e-mail: vaibhav.chaturvedi@ceew.in

estimates of mitigation potential, providing limited insight into how land-based carbon sequestration evolves over time as soils and forests approach biophysical limits. In particular, the durability of land-sector carbon sinks beyond a point, and the role of land management choices in sustaining sequestration under net-zero constraints, remain insufficiently explored. Additionally, the accuracy of emission estimations is often hindered by issues such as data availability and inconsistencies, leading to uncertainties in emission projection. Various studies have pointed out these challenges due to differences in research scope, methods of data collection, and resource limitations, particularly in developing countries like India^{25–30}. Moreover, inconsistencies in defining the time period required for soil to reach a steady-state condition in terms of carbon sequestration^{31,32} pose challenges in long-term emission projection.

Integrated assessment models (IAMs) are widely used to assess long-term emission pathways by capturing changing socioeconomic and policy factors (income, population, technological evolution, energy subsidies, carbon pricing)^{33–36}. Such frameworks are particularly well suited for analysing land-based mitigation, where carbon outcomes are shaped by cross-sectoral dynamics involving agriculture, forestry, and energy demand. In the Indian context, IAMs have been increasingly applied to explore energy transitions and climate policy pathways^{37,38}. However, their application to long-term land-use carbon dynamics remains limited, particularly with respect to soil carbon processes, forest maturity, and land management strategies.

To address this gap, this study employs the Global Change Analysis Model (GCAM, CEEW version), an integrated assessment model that captures interactions among socio-economic development, energy systems, agriculture, land use, and climate policy. The framework is extended to represent cropland soil organic carbon (SOC) dynamics, agroforestry systems, alternative FTC expansion pathways, net-zero transitions, and biophysical constraints that would influence India's long-term land-use emissions and carbon sequestration trajectories. In this context, the contribution of this work is threefold. First, it evaluates how key biophysical uncertainties associated with SOC saturation and forest maturity shape the evolution of land-based carbon sinks over time, moving beyond static or near-term estimates of mitigation potential. Second, it compares alternative pathways to demonstrate how land-use policy and management choices govern the durability of sequestration outcomes under fixed FTC targets while also affecting agricultural land availability and future food production. Third, it explicitly examines the offset potential of long-term land-use emission sequestration to counter-balance India's energy sector emissions under its 2070 net-zero pledge.

Our analysis shows that the magnitude and persistence of India's land-based carbon sink are highly sensitive to both scientific uncertainties and policy choices. We find that while accelerated FTC expansion can deliver high near-term carbon removals, a more gradual expansion pathway combined with agroforestry and rotational harvesting can sustain carbon sequestration over longer timescales. The results further demonstrate that uncertainty in forest biomass carbon density and cropland SOC leads to a wide range of projected sequestration outcomes. This highlights the fact that improved carbon monitoring and data is indispensable for robust estimation of land-based mitigation potential to inform policy decisions. Overall, the study shows that India is on track to achieve its 2030 forest-based NDC target and provides indicative upper and lower bounds for the contribution of the land-use sector to India's 2070 net-zero pathway.

Results

Land use change and associated emissions in the Reference scenario

We find that under the Reference scenario (refer "Scenario framework" in "Methods"), cropland would increase by 7% in 2050 compared to 2015 (42.5% to 45% of the total area), while it declines after 2050 due to a reduction in population-driven crop demand (Fig. 1a, b, c). If current trends persist, reaching the desired goal of increasing FTC area to 33% in the near future would be difficult. The area under FTC would increase slightly to

reach 27% of the total area by 2050, corresponding to an increase of about 12% relative to 2015, while by 2070 it would increase by an additional 1.6% points (28.6% of the total area; ~18% increase relative to 2015) (Fig. 1a, c). The additional land for the expansion of FTC and croplands is mostly provided by the other arable land (fallow land), which would decrease by 58% in 2050 and 70% in 2070 compared to 2015 (Fig. 1b, c). This makes it the dominant source of land reallocation under the Reference pathway.

The study finds that cropland is one of the major near-term contributors to land-sector carbon sequestration accounting for ~72% of total land-use carbon sequestration until 2030 (uncertainty range: 52–76%) (Fig. 2a). However, a decline in cropland sequestration is noticeable after 2030, dropping its share to 1% by 2070 (uncertainty range: 0.5–2.0%) and reaching near zero by the end of the century. This decline occurs because cropland soils gradually approach their steady-state SOC levels under the current management conditions, reducing annual carbon accumulation rates over time. Although land-use transitions, including conversion to cropland, are explicitly represented in the model, the additional SOC gains from newly converted cropland are insufficient to offset the declining sequestration rates across the larger existing cropland area.

FTC represents the second-largest share of land-use sector sequestration until 2035 in the Reference scenario. However, as cropland sequestration declines, reaching steady-state levels, FTC will become the primary contributor to the land-use carbon sink in the long run. In this scenario, the slow expansion of FTC areas (0.3% points annually based on historical trends) significantly limits additional sequestration. This, combined with declining sequestration rates from aging forests, leads to a pattern of reduced FTC-driven carbon sequestration over time. Furthermore, as cropland sequestration declines and existing FTC reaches maturity, the overall sequestration in this scenario declines beyond a point (Fig. 2a).

Notably, total land-use sector CO₂ sequestration varies substantially based on the uncertainty assumptions for biophysical factors (Low–Medium–High carbon density; SOC maturity at 50 years). Under the Reference scenario, the total net sequestration across all land-use categories is projected to reach 189 MtCO₂ yr^{−1} in 2070 with an uncertainty range of 109–270 MtCO₂ yr^{−1} as depicted in Fig. 2a and further documented in Supplementary Note 3–5. These results highlight an important trade-off within the land-use sector. While FTC and cropland expansion increases long-term carbon sequestration through biomass and soil carbon accumulation, sequestration for each parcel of land under new FTC or crops gradually declines as biomass and soil approach equilibrium conditions. Therefore, the net land-sector sequestration trajectory reflects the balance between increasing area and declining sequestration rate across land use systems.

Cropland expansion and subsequent carbon dynamics are driven by the demand for food and non-food agricultural commodities. In terms of food production, our findings indicate that non-staple crops would be the most consumed category in the future, with a projected demand of around 800 Mt by 2070 (Fig. 3a), up from 290 Mt in 2020. This would influence the production of vegetables, fruits, and legumes, with an annual growth rate of 1.7–2%. Feed crop demand is expected to rise more than double (from 236 to 527 Mt) at a rate of 1.5% annually between 2015 and 2070, resulting in a 68% increase in fodder crop production. Demand for biofuels and non-food items like cotton and jute is also anticipated to increase at a CAGR of 0.4% from 427 to 519 Mt over the period 2015–2070. It is worth noting that crop demand may increase rapidly until 2055 and then slow down due to the declining population. The future would witness a shift in the share of different crop types in production (million tonnes), with the share of sugar crops declining from 31% in 2015 to 28% in 2070 (Fig. 3b). Vegetables would become the second major crop, accounting for 20% of production, followed by fruits and legumes at 13% and 3%, respectively.

Implications of forest and tree cover (FTC) enhancement policy scenarios

India's National Forest Policy (1988) specifies a target of bringing 33% of the country's geographical area under FTC, but does not prescribe a timeline for

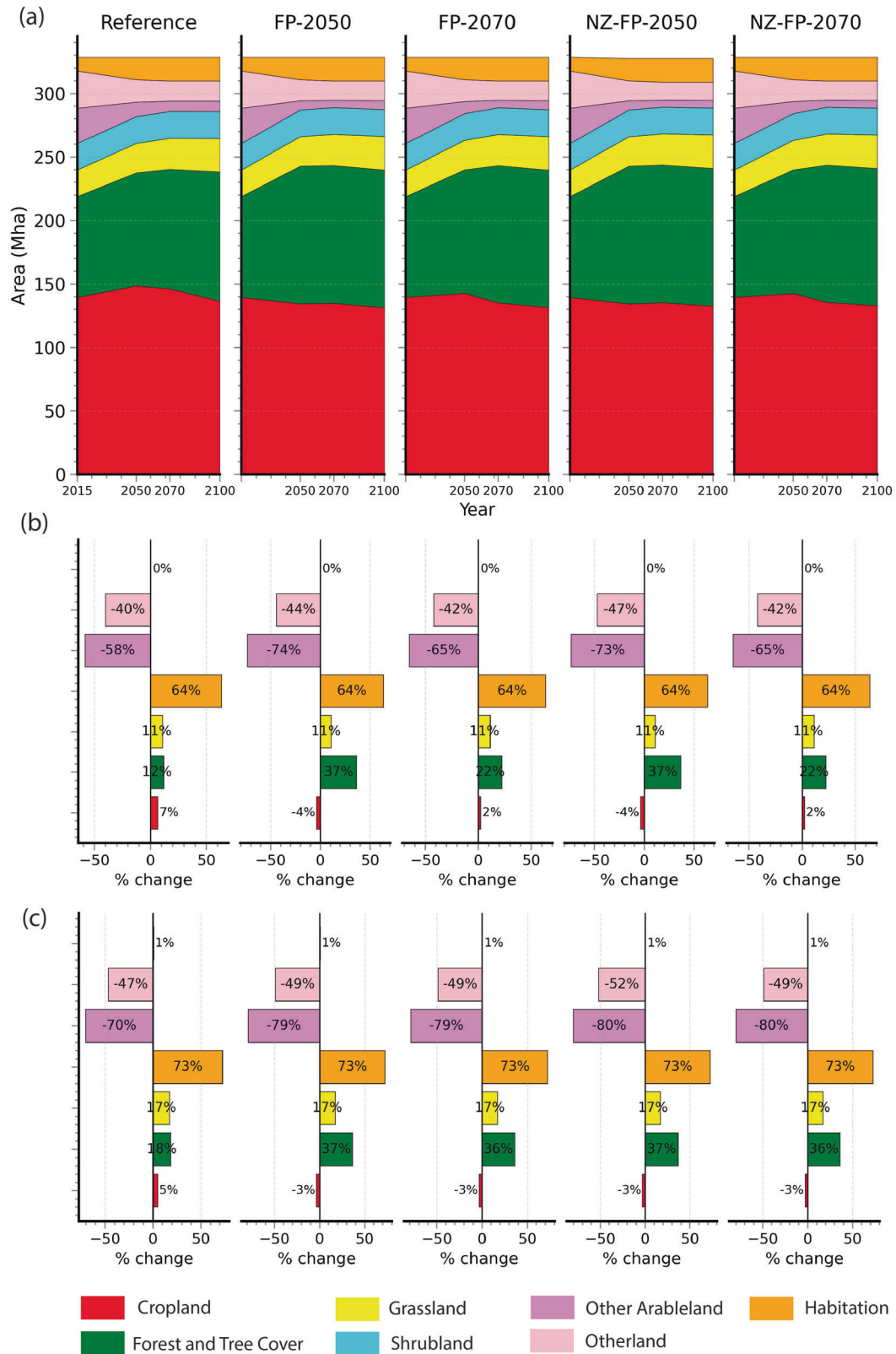


Fig. 1 | Projected land-use dynamics under alternative policy and net-zero scenarios. a Absolute land-use area (in million hectares, Mha) for major land-use categories from 2015 to 2100 under the Reference, FP-2050, FP-2070, NZ-FP-2050 and NZ-FP-2070 scenarios. **b** Percentage change in land-use area in 2050 relative to

the base year (2015). **c** Percentage change in land-use area in 2070 relative to the base year (2015). Detailed scenario definitions are provided in the “Scenario Framework” section of the “Methods” and methodological details on land allocation and policy constraints are described in the Supplementary Note 1.

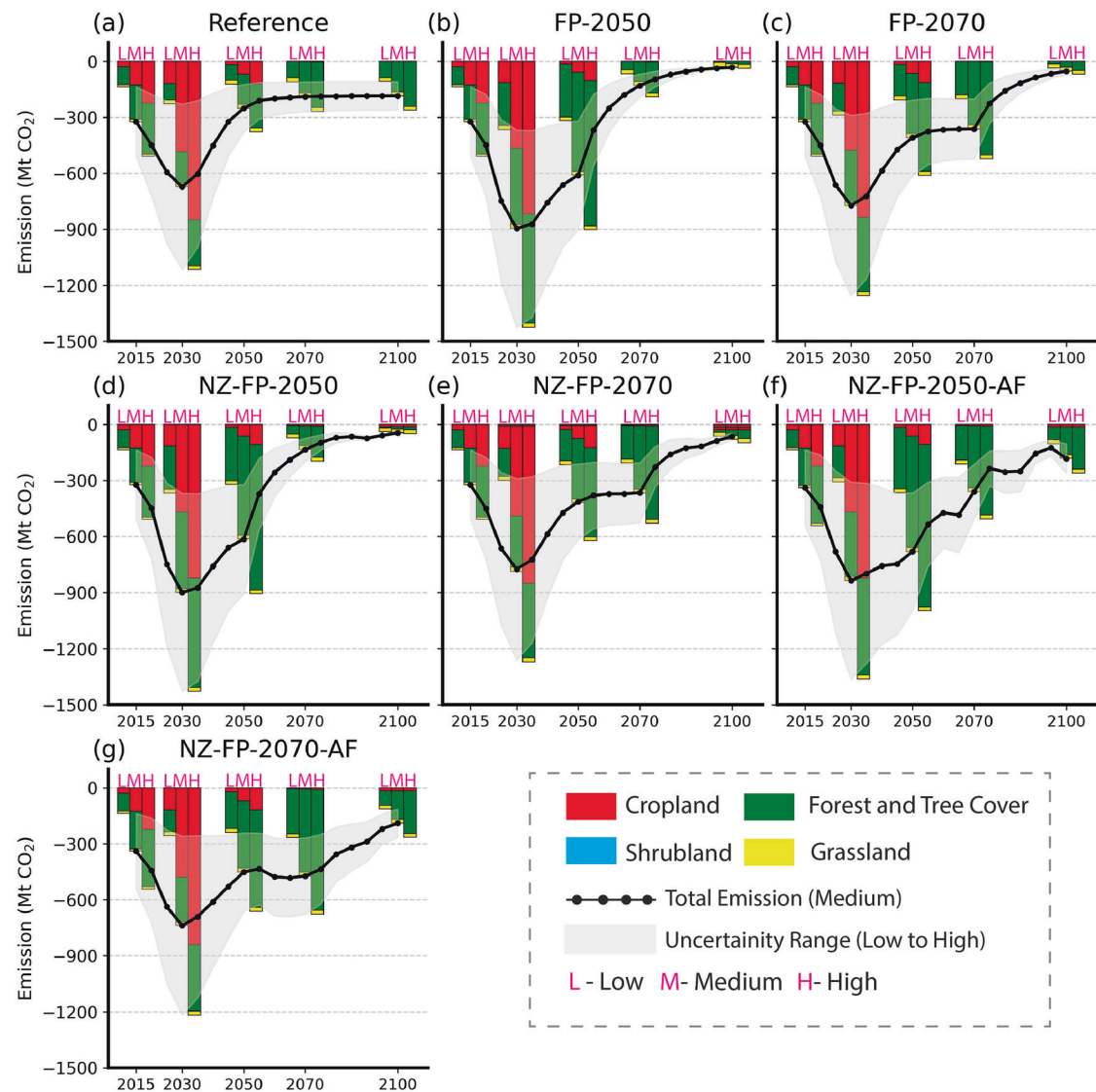


Fig. 2 | Projected land-use carbon emission trajectories under alternative policy and net-zero scenarios. **a** Annual land-use carbon emission trajectories under the Reference, **b, c** Forest Policy (FP), **d, e** Net-Zero Forest Policy (NZ-FP), and **f, g** agroforestry (AF) scenarios from 2015 to 2100. The FP scenarios represent pathways achieving India's 33% FTC target by 2050 or 2070, while the NZ-FP scenarios combine FTC expansion with economy-wide net-zero energy transition assumptions. The AF scenarios additionally incorporate rotational agroforestry systems with harvested wood product dynamics (see "Scenario Framework" in "Methods" for detailed scenario definitions). Coloured bars represent emissions or

removals from individual land-use categories. The thick black line represents total land-use sector CO₂ emissions under the Medium sequestration assumption, while the shaded envelope represents the uncertainty range bounded by the Low and High sequestration assumptions from alternative forest carbon density and cropland SOC assumptions described in "Methods" and Supplementary Note 3–5. In all the scenarios and results in the main text, cropland SOC is assumed to steady state conditions over a 50-year time period, with the 100-year sensitivity results presented in the Supplementary material.

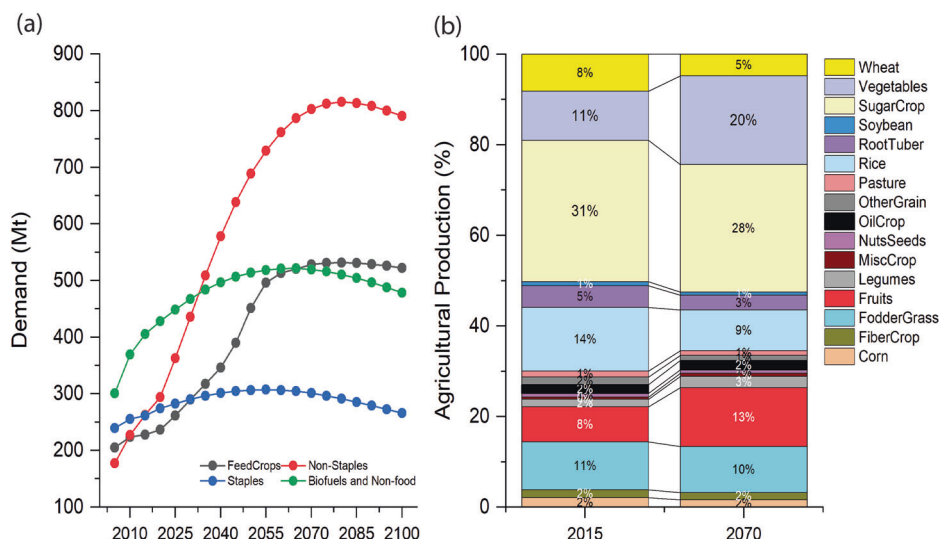
achieving this target. Therefore, we explore both an accelerated implementation pathway (2050) and a gradual implementation pathway aligned with India's net-zero target year (2070) to evaluate how the timing of FTC expansion influences long-term sequestration dynamics and land-use transitions.

Aggressive FTC policy (FP-2050) scenario. In the FP-2050 scenario, the policy goal of reaching 33% FTC by 2050 is set, which focuses on its rapid expansion until 2050 and the expansion stops once the target is achieved. This leads to major changes in land use and emissions as compared to the Reference scenario. The cropland that was found to be increasing in the Reference scenario decreases in FP-2050 by 4% in 2050 compared to 2015 (Fig. 1a, b). Other arable lands also decrease more rapidly than the Reference scenario. Such major changes in land use have

a substantial influence on the emissions. Under FP-2050, carbon sequestration in the forest driven by enhanced FTC by 2050 would increase up to 530 MtCO₂ Year⁻¹ (uncertainty range: 284–776 MtCO₂) which is ~3.3 times more than the sequestration in the Reference scenario for the same year (Fig. 2b and Supplementary Fig. 7). The cropland on the other hand decreases to compensate partially for increasing FTC and reducing the sequestration by 12% in 2050.

However, by 2050, the overall land-use sequestration based on the Medium sequestration assumption is projected to reach 610 MtCO₂ year⁻¹ (uncertainty range: 318–902 MtCO₂) (Fig. 2b). This represents an increase of ~143% compared to the Reference scenario (uncertainty range: 138–157%). However, as the expansion of FTC stops in 2050, the sequestration rate also declines significantly, continuing this trend through 2100. Notably, forest carbon sequestration experiences a fourfold to sixfold

Fig. 3 | Agricultural demand and crop production composition in India under the Reference scenario. a Projected demand for major agricultural use categories—staples, non-staples, feed crops, biofuels and other non-food uses—expressed in million tonnes (Mt). The constituent food items within each category are listed in Supplementary Fig. 3. **b** Percentage share of total agricultural production (%) across 16 major crop categories in India in 2015 and 2070, showing changes in production composition over time. The underlying drivers of these changes are discussed in Supplementary Note 1d.



reduction by 2070 and an even sharper decrease by 2100. Moreover, as forested land expands at the expense of cropland, total crop production is projected to be lower by 1.5% in 2030, 3.8% in 2050, and 3.5% in 2070 compared to the Reference scenario. Among individual crops, wheat experiences the most significant decline in production (−11%), followed by rice, other grains, soybean, (−10%), root tuber (−8.4%) and corn (−8.2%) (Supplementary Fig. 10). These declines in production may have implications for future trade dynamics, potentially leading to higher food prices and increased volatility in crop commodity markets.

Moderately aggressive FTC policy (FP-2070) scenario. The FP-2070 scenario takes a much slower approach compared to FP-2050 in expanding the FTC, targeting 33% of total land area by 2070. Therefore, by 2050, FTC is projected to cover 29.7% of the total land area which is 3.3% points less than the FP-2050 scenario (Fig. 1a). By 2070, area under FTC shows a net increase of ~33% relative to 2015, while cropland and other arable land decline by 3% and 79% (Fig. 1c). Hence, by 2050, the FTC-based sequestration would be 39% lower than the FP-2050 scenario (Fig. 2c and Supplementary Fig. 7). However, unlike FP-2050, where sequestration rates decline abruptly post-2050, FP-2070 sequestration continues steadily until 2070. After 2070, sequestration follows a decline pattern similar to the post-2050 period in FP-2050. As a result, the FP-2070 scenario achieves an annual sequestration of 362 MtCO₂ Year^{−1} (uncertainty range: 201–523 MtCO₂) in 2070 (Fig. 2c). This represents a 91% increase (uncertainty range: 84–94%) compared to the Reference scenario and a 178% increase (uncertainty range: 172–196%) compared to FP-2050. Total crop production in FP-2070 declines at a slower rate, reducing by 1% in 2030 and 3.5% by 2070 relative to the Reference scenario. Despite this gradual decline, the reduction in production of different crops by 2070 is more or less similar to that in the FP-2050 scenario (Supplementary Fig. 10), primarily due to the same reduction in cropland area under both scenarios.

Implications of net-zero energy with FTC policy (NZ-FP-2050 & NZ-FP-2070) scenarios

The NZ-FP-2050 and NZ-FP-2070 scenarios share the same goal as the FP-2050 and FP-2070 scenarios: achieving 33% FTC by 2050 and 2070, respectively. However, a key distinction is the inclusion of a net-zero target for 2070, specifically within the energy sector. Under Net-Zero scenario, there is an explicit CO₂ emissions cap on the energy system, which is met endogenously through a combination of energy efficiency improvements, fuel switching, and deployment of negative-emission technologies. In particular, bioenergy with carbon capture and storage (BECCS) emerges as a key mitigation option for offsetting residual

emissions from hard-to-abate sectors (Fig. 4a). As a result, the net-zero energy target implies higher zero-carbon bioenergy production through increased biomass cultivation, which could impact land use emissions. However, we find that net-zero energy target affects land use and associated emissions only slightly. Our results show that biomass area expands to 1.1 Mha by 2070 in the both the NZ-FP scenarios, taking much of the land from cropland and other arable land categories (Fig. 4b). While FTC emissions remain similar to those in FP scenarios, biomass cultivation in NZ-FP scenarios contributes to increased sequestration. Hence, the sequestration in NZ-FP-2050 is slightly higher (0.6%) than in FP-2050 (uncertainty range: 0.4–1.1%) by 2050 (Fig. 2d). In NZ-FP-2070, sequestration exceeds FP-2070 by 0.7–1.8% in 2070 (Fig. 2e). Overall, these results indicate that the primary role of bioenergy in the net-zero scenarios is to offset residual energy-sector emissions through BECCS, while their influence on land-use sequestration pathways remains limited. Essentially, deep emissions reductions in the energy sector do not materially impact India's land use emission trajectories.

Implications of agroforestry with rotation period on carbon sequestration

We show that, unlike afforestation without rotation periods, which exhibits a continuous decline in sequestration once afforestation targets are achieved by 2050 or 2070 (Fig. 2b–e), agroforestry with rotation periods sustains carbon sequestration even beyond the target years. In the NZ-FP-2050-AF scenario, annual sequestration across all land use categories is 360 MtCO₂ (uncertainty range: 213–508 MtCO₂ year^{−1}) in 2070 (Fig. 2f). Furthermore, after achieving the afforestation target, an average of 213 MtCO₂ (uncertainty range: 126–300 MtCO₂) sequestration continues annually till 2100, this is 2.4–3 times higher than the sequestration in conventional afforestation scenario (NZ-FP-2050). This sequestration is primarily driven by rotational harvesting and replanting when approaching a steady-state conditions, which maintains continuous carbon uptake in harvested wood product (HWP) and delaying the carbon emissions, contributing 68%–86% of total land-use sequestration (Fig. 2f) in 2100. In contrast, conventional afforestation without rotational agroforestry reduces this contribution to 13–30% across all categories in 2100. A similar trend is observed in the NZ-FP-2070-AF scenario, with annual sequestration rates of 473 MtCO₂ (uncertainty range: 268–678 MtCO₂), 29% higher than conventional afforestation in 2070 (Fig. 2g). However, after 2070, an average of 321 MtCO₂ year^{−1} (uncertainty range: 192–450 MtCO₂ year^{−1}) sequestration continues which is 2.1–2.2 times higher than the sequestration in the NZ-FP-2070 scenario by the end of the century.

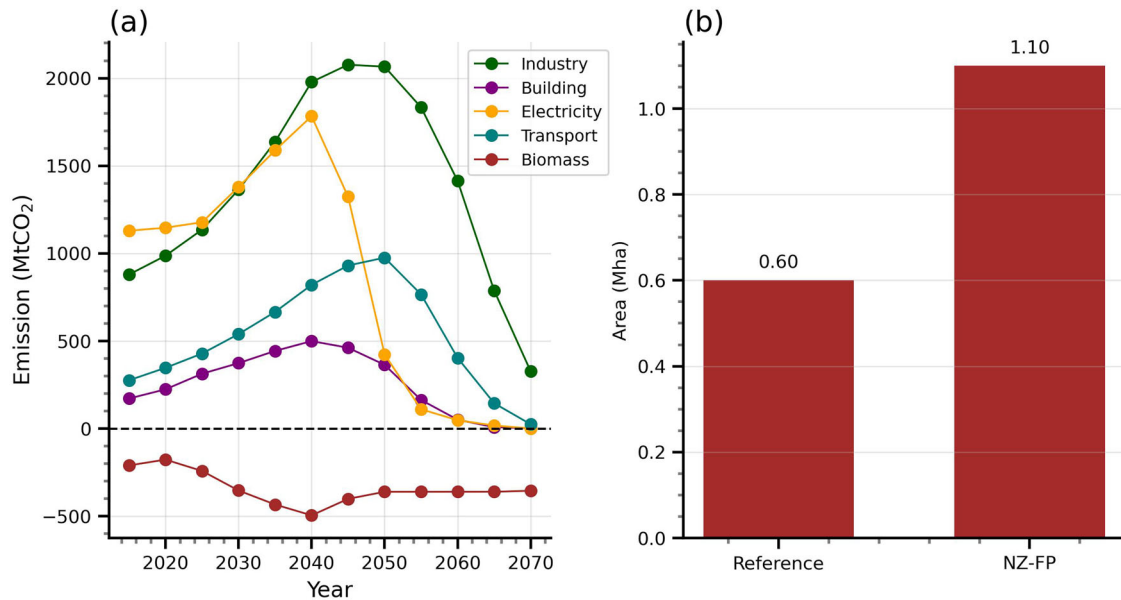
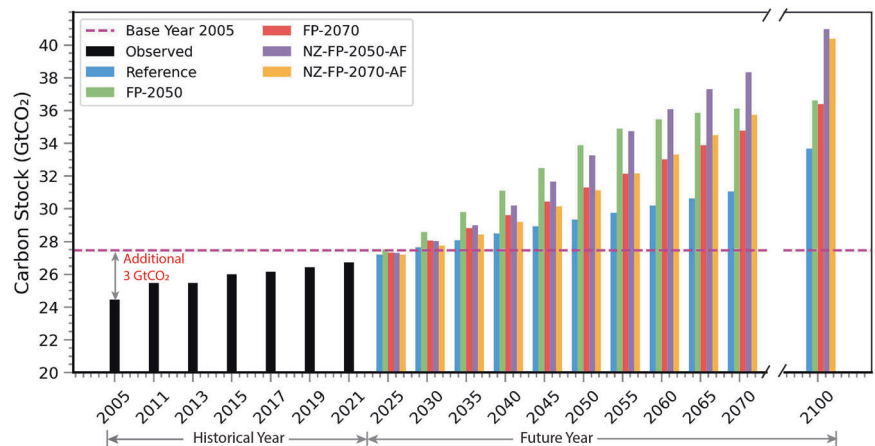


Fig. 4 | Role of biomass in offsetting residual energy-sector emissions under net-zero energy scenarios. **a** Residual CO₂ emissions from major energy-sector components—industry, buildings, electricity, and transport—together with negative emissions from biomass in the net-zero energy scenarios. Negative emissions represent CO₂ removals achieved through bioenergy with carbon capture and

storage (BECCS) and reflect energy-sector mitigation rather than land-use carbon stock changes. **b** Land area allocated to purpose-grown biomass crops in 2070 under the Reference and net-zero forest policy (i.e., NZ-FP 2050 and NZ-FP 2070) scenarios. Biomass crop area is drawn primarily from cropland category.

Fig. 5 | Projected forest and tree cover carbon stocks under alternative land-use scenarios.

Changes in carbon stock for India's Forest and Tree Cover land-use class under the Reference, FP-2050, FP-2070, NZ-FP-2050-AF and NZ-FP-2070-AF scenarios, using carbon density values from the Forest Survey of India (FSI; see Supplementary Table 7 for details). The short-term NDC target of achieving an additional 3 GtCO₂ by 2030 is shown relative to two different base years (2005) via horizontal dashed line. Black bars represent the observed carbon stock as reported by FSI, while blue, green, red, violet and yellow bars depict the projected carbon stock under the Reference, FP-2050, FP-2070, NZ-FP-2050-AF and NZ-FP-2070-AF scenarios, respectively.



Implications for forest carbon stock and short-term NDC target

The Government of India's NDC targets include the creation of an additional carbon sink of 2.5–3.0 GtCO₂ by 2030 relative to the 2005 base year^{8,39}. Our assessment (based on FSI carbon density data) shows that this target would be achieved in all the FTC expansion scenarios (Fig. 5). If FTC had increased even more aggressively (FP-2050), this target would have been achieved by 2025. It is also evident that a rapid increase in FTC under the FP-2050 scenario would create a significant carbon sink between 2021 and 2050 (an additional 7.2 GtCO₂) and this continues to grow even if the FTC expansion process stops after 2050. In contrast, the growth rate of carbon sequestration in FP-2070 is lower than that in FP-2050 until 2050. However, carbon sequestration keeps increasing post-2050 as well, leading to continued growth of the carbon sink. By 2070, the carbon stock stored in area under FTC under the FP-2050 scenario reaches 36.1 GtCO₂, while FP-2070 achieves 34.8 GtCO₂, a small difference. This difference arises because, under FP-2050, India's forest policy target is met earlier in 2050, allowing a longer period for carbon

accumulation, whereas FP-2070 meets the target only by 2070. However, by the end of the century, the carbon stock under both scenarios converges, with a negligible difference of 0.2 GtCO₂. A similar trend is observed under the 2070 net-zero energy sector scenarios combined with forest policy targets (NZ-FP-2050 and NZ-FP-2070). Notably, the NZ-FP-2050-AF and NZ-FP-2070-AF scenarios, which incorporate rotational harvesting, result in higher carbon stocks compared to conventional afforestation (FP-2050/NZ-FP-2050 and FP-2070/NZ-FP-2070). Under NZ-FP-2050-AF, an additional 14.3 GtCO₂ is sequestered between 2021 and 2100, representing a 44–48% increase relative to FP-2050 and FP-2070. Similarly, NZ-FP-2070-AF sequesters an additional 13.6 GtCO₂, corresponding to a 38–41% increase over the conventional afforestation scenarios.

The estimates presented in this section assume forest carbon densities as per FSI estimates, which are at the lower end compared to globally reported estimates. Using higher end values for forest carbon density show significantly higher sequestration and forest carbon stock as shown in the

uncertainty ranges presented in the conclusion section. Further explanation has been presented in Supplementary Note 3.

Discussion

Our study suggests that the timing and management of FTC expansion strongly shape the land-based carbon sinks under India's long-term net-zero strategy. We find that the FP-2050 pathway delivers higher sequestration in the near term ($610 \text{ MtCO}_2 \text{ yr}^{-1}$ by 2050), but experiences a rapid decline thereafter. In contrast, FP-2070 maintains sequestration growth for a longer period and achieves $362 \text{ MtCO}_2 \text{ yr}^{-1}$ in 2070, compared with only $130 \text{ MtCO}_2 \text{ yr}^{-1}$ under FP-2050 (Medium sequestration assumption). These findings suggest that the long-term effectiveness of FTC expansion depends not only on the area brought under FTC but also on the temporal profile of forest growth and carbon accumulation. This is because the carbon sequestration rates are generally highest during active growth phases and decline as forests mature, resulting in lower annual removals despite continued storage of carbon in biomass. Similar age-dependent sequestration patterns have been reported across a wide range of forest ecosystems^{40–43}. Importantly, our analysis further indicates that these age-structure effects interact with saturation dynamics in other land-use categories, particularly cropland soils, where SOC accumulation typically peaks in the first few decades and declines as soils approach steady-state conditions, a finding consistent with other studies^{44–46}. These findings are particularly important in the context of India's net-zero strategy, where land-based removals are expected to offset residual emissions from hard-to-abate sectors. Our results suggest that relying on static assumptions of constant annual sequestration within soil and biomass may overestimate the long-term mitigation contribution of the land sector. Instead, sequestration trajectories evolve dynamically over time due to interactions between forest maturity, cropland soil carbon saturation, and land competition. In this context, our assessment also highlights that FTC expansion combined with the agroforestry with rotation period is critical for sustaining long-term carbon removals beyond 2070, as the system maintains a structurally durable sink even after area expansion stops. For example, NZ-FP-2070-AF maintains approximately $321 \text{ MtCO}_2 \text{ yr}^{-1}$ of sequestration after 2070, compared with much lower levels under conventional afforestation pathways. Agroforestry enhances mitigation durability through the harvested wood products (HWP) pool, where a portion of harvested carbon is stored in long-lived products and released gradually according to first-order decay dynamics^{47,48}. Studies also suggest that extending the life-span of HWPs can substantially increase cumulative carbon storage and may exert a stronger influence on mitigation outcomes than variations in harvest intensity^{49,50}. In addition, HWP can substitute emissions-intensive materials such as cement and steel, generating avoided fossil emissions through material substitution—a mitigation pathway widely recognised in global assessments^{51,52}.

While FTC-driven CO_2 sinks can help offset residual energy-sector emissions, non- CO_2 emissions (particularly from agriculture) are expected to persist, and land-based removals are subject to uncertainty, saturation and disturbance risks over long-time horizons^{53,54}. The decline in sequestration once large forest cohorts mature also addresses concerns around mitigation deterrence, whereby expectations of future land sinks could delay decarbonisation in energy and industrial systems^{55,56}. Essentially, having 33% land area under forest cover wouldn't necessarily lead to high sequestration for ever and can not compensate for a lack of deep near and long-term mitigation in the energy systems. Moreover, because residual emissions are concentrated in urban and industrial sectors while land-based sequestration is largely delivered through rural landscapes, these pathways raise important questions regarding the distribution of mitigation burdens and co-benefits in agrarian economies such as India^{53–57}.

It is worth noting that agroforestry with rotational tree planting considered in this study is established on cropland, fallow land and other suitable agricultural lands, rather than through the harvesting or conversion of natural forests. Therefore, the associated ecological trade-offs differ from intensively managed forest systems. Well-managed agroforestry can improve soil health, biodiversity, and other ecosystem services compared

with conventional agriculture^{58–60}. As these outcomes vary with species composition, management practices, and landscape context, the carbon mitigation potential presented here should be considered alongside broader ecological and socio-environmental objectives when designing land-use policies.

The land-use transition pathways considered in this study have been prepared following the existing policy commitments, technical potential and implementation evidence in India. We further assess their practical feasibility dimensions following the proposed IPCC SR1.5⁶¹ framework. From a scale perspective, the scenarios require FTC to increase from 80.95 Mha in 2020 to 108.44 Mha , corresponding to annual expansion rates of 0.92 Mha yr^{-1} (FP-2050) and 0.55 Mha yr^{-1} (FP-2070). These rates are within the range of the average annual FTC expansion ($\sim 1.65 \text{ Mha yr}^{-1}$) inferred from the area required to achieve India's NDC sink target during 2015–2030⁶². Furthermore, the total expansion required (27.49 Mha) remains substantially lower than the 55.76 Mha of suitable wasteland and fallow land identified by NITI Aayog's GROW⁶³ assessment for agroforestry expansion. Since the National Forest Policy (1988)⁹ specifies the 33% FTC target without prescribing a target year, the 2050 and 2070 scenarios represent alternative implementation pathways rather than fixed policy commitments. Similar variation is already evident across Indian states. For example, Telangana adopted an accelerated afforestation pathway through “*Telanganaku Haritha Haram*”⁶⁴, whereas Tamil Nadu's *Green Tamil Nadu Mission*⁶⁵ aims to achieve 33% green cover by 2030–31 through phased afforestation and agroforestry expansion. Technically, the scenarios rely on established agroforestry systems and existing institutional mechanisms under the National Forest Policy. India's NDC and the Green India Mission and require no unproven technology. Taken together, these considerations suggest that the modelled transition pathways are realistic in terms of their scale, technical basis and policy direction. However, their successful implementation will depend on sustained farmer participation, favourable market incentives, effective governance, and the long-term survival of planted trees⁶⁶.

Beyond policy and management choices, our results also highlight that scientific uncertainties substantially influence the magnitude of projected land-use carbon sequestration. A key source of this uncertainty arises from the large disparities between the carbon density values reported by the FSI and those available from global datasets. Global datasets⁶⁷ reported carbon density values which are approximately 2.7 times higher than the country-specific values⁶⁸ for similar vegetation categories, leading to substantial differences in overall emission estimates for all the scenarios considered in the study. In addition to forest carbon density uncertainty, cropland SOC represents a major source of uncertainty in land-sector mitigation assessments. While several studies have identified SOC as one of the largest sources of uncertainty in land-based mitigation assessments^{69,70}, our analysis demonstrates how these uncertainties translate into materially different long-term sequestration outcomes at the national scale. Given that croplands contribute a substantial share of near-term sequestration in several scenarios, uncertainty in SOC density and dynamics can significantly affect overall mitigation estimates. These uncertainties highlight the need for improved, land-use-specific carbon density datasets and consistent national monitoring frameworks to support robust planning and policy design.

In addition to uncertainties in carbon estimation, our findings suggest that long-term mitigation strategies should extend beyond FTC expansion alone. While policy discussions often focus on forest expansion as the primary mechanism for increasing land-based carbon sinks, our results indicate that cropland soils play an important role in the near term. Cropland SOC accounts for $\sim 72\%$ of total land-sector sequestration until 2030, making it the dominant contributor. However, this contribution declines sharply over time as soils gradually approach steady-state conditions. Similar saturation behaviour has been reported across a wide range of agricultural systems^{44–46,71,72}. Therefore, maintaining the mitigation contribution of agricultural landscapes will require continued adoption of practices that increase SOC stocks, including reduced tillage, residue

retention, cover cropping, diversified cropping systems, and agroforestry integration. Even though the climate smart agriculture practices are steadily making progress in this direction, ensuring that soil carbon is regularly measured and monitored to enhance not just sequestration but soil health and crop productivity would be critical for India. Besides agriculture, literature shows that land uses like grasslands, wetlands, and shrublands have a great potential to sequester carbon from the atmosphere into the soil³⁶, a finding also supported by our assessment. However, it is critical to think beyond carbon. For instance, open natural ecosystems (encompassing semi-arid savanna grasslands, and savanna woodlands, along with rocky outcrops and other naturally tree-less or sparsely vegetated geological features) as a critical ecosystem category⁷³. Hence, the Government of India is taking major initiatives to protect grasslands, wetlands and shrublands of the country to promote its long-term low-carbon development strategy and biodiversity conservation⁷⁴. It is important to emphasize that these lands are not diverted for afforestation solely for the purpose of carbon sequestration, which should take place primarily in lands specifically identified for this purpose (e.g., wastelands and fallow lands).

Although these findings provide useful insights into the role of different land-use systems, future climate change may further influence long-term sequestration trajectories. In our assessment, the variation in carbon sequestration observed across scenarios is mainly due to the growth stages of forests, where young forests absorb carbon more rapidly than mature forests. However, a few studies indicate that old-growth forests also sequester carbon beyond their growth phases and play a crucial role in climate change mitigation^{75–77}. In this case, several factors contribute to this process, including extended growing seasons due to climate change⁷⁸, successional dynamics⁷⁹, species composition⁸⁰, carbon fertilization from fossil fuel emissions⁸¹ and nitrogen deposition-induced nutrient fertilization^{75,82}. Although the contribution of old-growth forests to carbon sequestration is relatively small, their role as carbon sinks should not be overlooked in climate mitigation strategies. Currently, GCAM does not explicitly model various ecological processes influencing forest carbon sequestration, but considers the fact that old forests sequester carbon at low rates. Apart, this study has not accounted seasonal and inter-annual variability of the carbon sequestration rate which can be strongly influenced by environmental and climatic factors such as droughts, wildfires, and extreme weather events including El Niño^{83–85}. The increasing frequency of such extreme events due to climate change poses a serious risk where biomass gains may be offset by disturbance-related losses. Taken together, while land-based mitigation remains central to India's net-zero vision, the sequestration potential will depend not only on policy-driven expansion of forests and agroforestry but also on how climatic drivers interact with ecological processes. Strengthening long-term monitoring networks (e.g., flux towers, soil carbon observatories) is therefore essential to reduce uncertainty and refine projections for policy planning.

While our analysis focuses on India, the findings have broader relevance for countries pursuing land-based CDR as part of their mitigation strategies. Net-zero pathways assessed by IAMs commonly depend on afforestation, reforestation, ecosystem restoration and bio-energy systems to offset residual emissions from hard-to-abate sectors^{86–88}. Countries such as China, Brazil, Indonesia, Canada and several African nations have also identified land-based removals as important components of their long-term climate strategies. However, recent studies have highlighted concerns regarding the permanence, scalability, and uncertainty of land-sector carbon sinks, as well as inconsistencies between national inventories and IAM representations of land-use mitigation^{89–91}. Our results contribute to this broader discussion by demonstrating that sequestration outcomes depend not only on land-cover targets but also on biophysical limits, forest age structure, soil carbon saturation and management practices. By integrating these processes within an IAM framework, the study provides a transferable approach for improving the representation of land-based mitigation and evaluating the durability of CDR pathways in countries seeking to balance net-zero ambitions with food security and land-use constraints.

Limitations

While our study provides valuable insights into future carbon sequestration and emissions in the land use sector for India, it does have some limitations. First, IPCC methodologies typically consider SOC at 0–30 cm depth, whereas in this study, due to the lack of consistent and reliable India-specific datasets at shallower depths, SOC estimates at 0–100 cm depth have been used. As SOC concentrations are known to decline with depth⁹², the inclusion of deeper soil layers in our analysis may lead to a slight over-estimation of total SOC sequestration. In addition, there is a lack of sufficient ground sampling SOC data for the cropland category for a particular year, which can be used for selecting the base year for SOC sequestration projections. Second, our study has not captured the reversibility of carbon sinks from soil carbon sequestration (SCS), in other words the potential for SOC to become a source post reaching the steady-state condition has not been examined. A failure to properly manage cropland SOC can lead to it becoming a net carbon source, particularly due to land-use changes or intensive agricultural practices^{4,70,93}. Third, our modelling framework does not explicitly account for climate-carbon feedbacks associated with changing atmospheric CO₂ concentrations⁸¹, climate extremes and disturbance regimes^{83–85} or overshoot trajectories. Carbon sequestration dynamics in our assessment are primarily driven by land-use transitions, management assumptions, and forest age structure. As a result, potential climate-driven changes in vegetation productivity, forest mortality and soil carbon dynamics are not represented and could influence the magnitude and persistence of long-term carbon sinks. This omission of climate-driven uncertainty in carbon stocks is a notable gap that future research should address, ideally through coupling with dynamic global vegetation models or Earth system models. Lastly, India has potential to enhance carbon sequestration through the densification of existing forests via regeneration efforts, which has not been included in our study. According to FSI (2021) report⁶⁸, 43% (30.7 Mha) of the total forest cover (71.4 Mha) is categorized as Moderately Dense Forest (MDF), and another 43% (30.7 Mha) as Open Forest (OF). These areas could hold considerable potential for increasing carbon sequestration if OF areas are converted into MDF and MDF areas into Very Dense Forests through forest regeneration processes.

Conclusions

As India pursues its NDC commitments and long-term net-zero goal, understanding the magnitude, durability, and uncertainty of land-based carbon sequestration becomes increasingly important. This study addresses a critical gap in India's climate policy by integrating land-use transitions, soil carbon dynamics, forest carbon accumulation, and energy-land interactions within a single modelling framework tailored to Indian conditions.

We find that the land-use sector can provide a substantial contribution to climate mitigation, but that contribution is neither fixed nor permanent. Carbon sequestration depends not only on the extent of FTC expansion, but also on the biophysical and temporal dynamics of forests and cropland soils, which gradually reduce sequestration rates as these systems mature. Therefore, long-term mitigation assessments must move beyond static estimates of carbon sink potential and explicitly account for how sequestration evolves over time.

Our analysis further highlights that pathway design and management strategy matters. Alternative approaches to achieving the same FTC target can lead to different land use allocation and carbon sequestration pattern. In this context, agroforestry-based systems provide an opportunity to sustain carbon uptake beyond the period during which conventional afforestation delivers its strongest gains.

A central finding of this study is the large influence of scientific and policy uncertainty on projected land-use sequestration. Differences in carbon density estimates, cropland SOC maturity years and policy choices (33% FTC target year, agroforestry regime) produce a wide range of sequestration values by 2070 (Table 1), which provides indicative lower and upper bounds for the contribution of the land-use sector to India's net-zero pathway for 2070 and the level of residual emissions that could potentially be balanced through land-based removals. It should be emphasised that

Table 1 | Projected land-use sector (LULUCF) carbon sequestration in 2070 (MtCO₂ yr⁻¹) under alternative forest policy, net-zero, and agroforestry pathways, and across key scientific uncertainty assumptions

Carbon densities Cropland SOC maturity year	Scientific uncertainties					
	Low		Medium		High	
	50 years	100 years	50 years	100 years	50 years	100 years
Policy uncertainties (Scenarios)						
Reference	109	114	189	210	270	305
FP-2050	68	72	130	148	192	224
FP-2070	201	205	362	380	523	555
NZ-FP-2050	73	77	135	154	198	230
NZ-FP-2070	205	209	366	384	527	568
NZ-FP-2050-AF	213	217	360	379	508	540
NZ-FP-2070-AF	268	272	473	491	678	719

Forestland SOC takes very long (~500 years)²⁵ to mature, hence that sensitivity has not been analysed. *Scenario definitions:* Reference = business-as-usual; FP-2050 = FTC target of 33% achieved by 2050; FP-2070 = FTC target of 33% achieved by 2070; NZ-FP-2050 = net-zero energy pathway with FTC target achieved by 2050; NZ-FP-2070 = net-zero energy pathway with FTC target achieved by 2070; NZ-FP-2050-AF = NZ-FP-2050 with agroforestry and rotational harvesting; NZ-FP-2070-AF = NZ-FP-2070 with agroforestry and rotational harvesting. For more scenario related information, please refer to scenario description in “Methods”.

Policy scenarios differ in the timing of achieving India's forest and tree cover (FTC) target of 33% land area, the inclusion of a net-zero energy pathway, and the adoption of agroforestry with rotational harvesting. Scientific uncertainties reflect alternative assumptions regarding soil and biomass carbon density and cropland soil organic carbon (SOC) maturation times.

though physical sequestration trajectories will extend much beyond 2070 as has been shown in our results (Fig. 2), we highlight the results for 2070 in our conclusion given the importance of this year from India's climate policy perspective. Reducing the scientific uncertainties through improved monitoring and nationally consistent carbon datasets will therefore be essential for strengthening future climate planning.

For India's net-zero target year (2070), longer duration to achieve cropland SOC maturity, higher carbon densities of soil and biomass, longer duration of FTC target year (2070 over 2050), and an agroforestry-based land management approach would lead to higher sequestration of carbon dioxide in the year 2070. On the other hand, the opposite of these would lead to a much lower sequestration by India's land systems. While two of these are scientific uncertainties that need to be understood better, the other two are policy choices that need to be carefully calibrated. Interestingly, our analysis finds that deep emissions reductions in the energy sector, while having implications for land-use change if bio-energy is pursued as a key strategy, do not materially impact India's land use emission trajectories.

Our analysis also shows that the current rate of expansion of FTC will lead to achievement of India's NDC pledge of additional carbon sink of 2.5–3.0 GtCO₂ by 2030 relative to the 2005 base year. Across the full ensemble of uncertainty scenarios, cumulative carbon removals over the 2015–2100 modelling horizon span are projected to reach 10.5–39.8 GtCO₂ for the FTC sector and 14.8–60.8 GtCO₂ across all land use categories, reflecting the wide range of mitigation outcomes under different management and uncertainty scenarios. By 2100, carbon stock of India's FTC (including both soil and vegetative carbon) is projected to range from 36.5 to 65.8 GtCO₂. Overall, the study suggests that the land-use sector can play a significant role in supporting India's transition to net zero, including achievement of its forest-based NDC target and creation of significant carbon stocks. However, its long-term contribution will depend on balancing forest expansion with agricultural needs and sustaining carbon uptake through appropriate land management. These findings provide a more

comprehensive basis for evaluating the role of land-based mitigation in India's long-term climate strategy.

Methods

This study applies the GCAM⁹⁴ to assess long-term land-use emissions and carbon sequestration pathways for India under alternative forest policy and net-zero scenarios. The methodological framework consists of three components. First, GCAM is used to represent the integrated interactions between socio-economic drivers, agriculture, land-use change, energy transitions, and carbon emissions. Second, study-specific add-on modules are developed to improve the representation of cropland SOC dynamics and agroforestry-based sequestration pathways. Third, scenario assumptions, key sources of biophysical and data-driven uncertainty analysis, and India-specific parameterisation are incorporated to evaluate the implications of alternative forest and energy transition pathways for India's long-term net-zero goals. The detailed structure of the modelling framework, assumptions, and analytical workflow is described in the following subsections and Supplementary Note 1–5.

Integrated assessment modelling for capturing land use transition emissions

The GCAM (V6.0) evaluates different mitigation policies focusing on agriculture, land use and terrestrial carbon cycle modules⁹⁴. GCAM is a dynamic recursive model that integrates socio-economy, energy, water, land, and climate systems. It balances supply and demand across these sectors using a market-equilibrium approach and runs globally across 32 regions, including India, from 2015 to 2100 with 5-year steps. The GCAM default reference scenario adopts population and Gross domestic product (GDP) projections from the Shared Socioeconomic Pathway “Middle-of-the-Road” scenario^{95,96}. However, to align with the region-specific projection, we have calibrated the model using India-specific socio-economic factors (e.g., population, GDP), agriculture, land use types, and other relevant economic and environmental variables.

Within GCAM, land-use change and associated carbon emissions arise from the interaction of several integrated model components. Socio-economic drivers such as population growth and income shape demand for food, biomass and energy. Land allocation across competing uses is determined through an economic competition framework based on relative profitability, while policy constraints are applied exogenously to reflect national land-use targets⁹⁴. Within this framework, agricultural demand, including both staple and non-staple crops, responds endogenously to socio-economic drivers and relative prices. While future agricultural demand may, in principle, be influenced by policy-driven or behavioural shifts in dietary preferences, no exogenous dietary changes or food-demand-side interventions are imposed in this study. Instead, all the key socio-economic, agricultural, and land-use parameters are calibrated to India-specific base-year to ensure consistency with national conditions. In addition, the biophysical parameters, including vegetation and soil carbon densities and carbon maturation dynamics, govern the magnitude and timing of carbon fluxes associated with land-use transitions. A detailed description of these drivers, assumptions, and parameterisations is provided in Supplementary Note 1. However, additional details on the structure and functioning of GCAM's land-use component are available in the model documentation and published studies^{94,97}. Notably, throughout this study, emissions and sequestration refer only to carbon dioxide (CO₂), which aligns with the aim of our study. This is due to two reasons. First, this scope aligns with India's long-term net-zero target for 2070, where mitigation of agricultural non-CO₂ emissions (CH₄ and N₂O) is not included within the official net-zero target, and is addressed through separate sectoral strategies as a part of India's domestic policies⁹⁸. Second, non-CO₂ agricultural emissions are flow-based processes governed by distinct management and emission-factor uncertainties that are analytically different from stock-based CO₂ sequestration dynamics. We have therefore excluded here to maintain analytical focus on land-based CO₂ sequestration dynamics and to avoid introducing additional uncertainties related to non-CO₂ emission

factors, management-specific responses, and mitigation technologies within the context of India's net-zero goal.

Add-on module for capturing annual cropland carbon sequestration

GCAM captures carbon emissions and sequestration from land-use transitions and carbon vintages in forests, shrublands, and grasslands, but does not account for emissions or sequestration from long-standing cropland with annual harvest cycles. For example, if cropland increases from 140 to 150 Mha, GCAM models only the 10 Mha transition, ignoring the existing 140 Mha. In contrast, for forests, GCAM captures both the transition area and ongoing sequestration from existing forests using a vintage modelling approach, as forests have a lifecycle of more than one year, unlike annually harvested cropland. To address this limitation, we developed an add-on module that explicitly represents SOC dynamics across the entire managed cropland area, rather than restricting cropland carbon accounting to land-use transitions alone. This approach is consistent with national GHG inventory methodologies reported in the India's Third National Communication and Initial Adaptation Communication (TNC-IAC)⁹⁸, which assess cropland SOC stock changes at the system level. In the national GHG inventory⁹⁸, cropland sequestration sources have been divided into two components: vegetative biomass within tree outside forest (TOF) areas, and SOC. Since the sequestration related to TOF is included under the forest category in this study, the add on module focuses solely on cropland SOC sequestration.

Even though process-based SOC models^{99,100} can project future SCS, their application at the national scale requires extensive, spatially explicit data on climate, soil properties, and management practices, which are not consistently available for India. Therefore, we adopt a simplified sigmoid-based empirical approach⁴⁴, which has been widely used in the literature^{101–104} to capture non-linear SOC dynamics and saturation behaviour. This enables a scalable and policy-relevant representation of SOC change. (Eq. (1)).

$$SOC = SOC_0 + \frac{a}{1 + e^{\frac{t-t_0}{b}}} \quad (1)$$

SOC_0 represents the initial SOC density (mean SOC value), while a (the difference between mean and steady-state SOC value) and b are empirical constants, and t denotes time in years. The variable t_0 marks the year when the sigmoid curve's slope is steepest, indicating the highest annual sequestration rate.

Estimating steady-state SOC levels for different land-use types in India is challenging due to the absence of nationally representative equilibrium SOC data. The only India-specific assessment¹⁰⁵ provides observed mean SOC stocks at 100 cm depth but does not report SOC variability, distributional shape, or steady-state conditions required for modelling SOC dynamics over time. In contrast, global datasets such as SoilGrids¹⁰⁶ provide spatially explicit SOC distributions but systematically overestimate mean SOC levels for India when compared with national estimates. As a result, neither dataset alone is sufficient for deriving realistic steady-state SOC levels.

To address this limitation, we adopt a two-step distribution-based proxy approach^{107,108}. First, the Global SoilGrids dataset¹⁰⁶ is used to characterize the statistical distribution of SOC across land-use categories (e.g., gamma or Weibull distributions), capturing the variability in SOC across landscapes without directly using its mean values. Second, these distributions are recalibrated using India-specific observed mean and minimum SOC values¹⁰⁵, thereby anchoring the resulting SOC levels to nationally reported magnitudes. Near-equilibrium SOC is then represented by the upper quantile of the recalibrated distributions, reflecting long-term SOC potential under stable land-use conditions. Uncertainty in these estimates is explicitly explored through sensitivity analysis. A detailed description of the data sources, distribution fitting, recalibration procedure, and uncertainty assessment is provided in Supplementary Note 2 and 4.

Finally, to ensure consistency with national inventory estimates, the parameters of the SOC module are calibrated such that simulated cropland SOC stocks and sequestration rates in the initial and recent historical periods align with values reported in TNC-IAC⁹⁸. This calibration provides a realistic starting point for forward projections of SOC dynamics under alternative land-use and policy scenarios.

Add-on module for agroforestry with rotational period

Agroforestry represent a distinct land-management pathway in India, where rotational harvesting is commonly practiced in agroforestry and TOF systems managed by farmers, while forest lands are primarily managed for conservation with restricted commercial harvesting. India's agroforestry expansion plan aims to increase its area from 25 to 53 million hectares on the TOF area for environmental, economic, and social benefits^{109,110}. This also aligns with India's National Forest Policy goal of achieving 33% FTC and short-term NDC target of sequestering an additional 2.5 to 3 GtCO₂⁸ by 2030. The idea of expanding agroforestry is to integrate the timber and fruit-bearing trees with crops not only to enhance carbon sequestration and increasing farmers' income but also to support climate-resilient farming practices for smallholder systems¹¹¹.

Importantly, the introduction of agroforestry represents a change in land management, under which SOC transitions toward a new equilibrium, with active sequestration occurring during this adjustment period. Besides, the rotation period in the agroforestry system plays a vital role for supplying timber, ensuring continuous carbon sequestration and generating farmer income¹¹². But this depends on the functional characteristics of tree species used in agroforestry systems. Explicitly simulating individual tree species would introduce substantial uncertainty and complexity to robustly parameterized at the national scale. Therefore, this study represents agroforestry systems using three stylised rotation classes (short, medium, and long), which capture the dominant functional types of agroforestry practiced across India¹¹³ and the range of management choices commonly adopted by farmers, while maintaining tractability for integrated assessment modelling.

For example, short rotation agroforestry (~ 5 years) is mostly suited for fast-growing species like *Leucaena leucocephala* for fodder and soil improvement, while medium rotation (~ 15 years) is best for species like *Dalbergia sissoo* for timber and fuelwood. On the other hand, long rotation systems (30 years) prioritize high-value trees like *Tectona grandis* (teak) and *Mangifera indica* (mango) for timber, fruit and other ecosystem services¹¹³. These rotation classes therefore represent functional differences in growth rates, harvest cycles, and carbon accumulation, rather than fixed species choices.

In this module, SOC dynamics are represented using the same sigmoidal function applied to cropland, reflecting a gradual adjustment toward a new equilibrium following a change in management. In contrast, vegetative biomass sequestration is explicitly governed by the rotation period, as repeated harvest-regrowth cycles alter both the timing and magnitude of biomass carbon accumulation. By incorporating this rotation framework, the objective of this add-on module is to distinguish tree-based systems characterised by repeated harvest-regrowth cycles from non-rotational afforestation representations commonly used in IAMs. This enables a consistent assessment of how alternative agroforestry management choices influence long-term carbon sequestration outcomes while remaining suitable for national-scale analysis. However, it should be noted that in this study, the standard economic land-allocation mechanism of GCAM is overridden for the expansion of FTC, as the increase in FTC is treated as a policy-driven regulatory target rather than an outcome of market-based land competition. Accordingly, the additional land required to meet the FTC target is imposed exogenously in the model, consistent with India's forest policy framework (Supplementary Note 1c). The agroforestry add-on module is then applied to this additional FTC area and is used to evaluate alternative management strategies within the same land base, focusing exclusively on their implications for carbon sequestration. As such, costs associated with agroforestry establishment, management, harvesting, and replanting are not explicitly modelled in this module. Other land categories

like cropland continue to be driven by a competitive framework. To account for this, we adjusted the vegetative carbon sequestration equation¹¹⁴ with additional rotation period parameters (Eq. (2)):

$$CS_y^{\text{veg}} = CS_t^{\text{veg}} \times \left[\left(1 - e^{\frac{-3.0(y-t+1)}{M}} \right)^2 - \left(1 - e^{\frac{-3.0(y-t)}{M}} \right)^2 \right] \quad (2)$$

CS_y^{veg} : CS indicates net carbon sequestration in the vegetative biomass due to a land use change in timestep t , where t is the time of land conversion, y is the current year, M is the mature age.

After each harvesting period (at the end of the rotation period), for short (~ 5 years), medium (~ 15 years), and long (~ 30 years) rotation, t is reset to the current year y to start the sequestration process from the beginning.

To capture post-harvest carbon dynamics, a portion of the harvested biomass is transferred to a harvested wood product (HWP) pool and modelled using the IPCC first-order decay approach Eq. (3) consistent with the IPCC 2006 Guidelines and 2019 Refinement^{47,48}.

$$C_i(i+1) = e^{-k} \cdot C_i(i) + \left[\frac{1 - e^{-k}}{k} \right] \cdot \text{Inflow}_i(i) \quad (3)$$

$C_i(i)$ = carbon stock in product pool in year i ,

$\text{Inflow}_i(i)$ = carbon entering product pool in year i ,

$k = \ln(2)/\text{HL}$,

HL = half-life of product category

The term $\frac{1 - e^{-k}}{k}$ adjusts annual inflow for continuous decay over the accounting period.

This formulation ensures that harvested carbon initially contributes to a sink via product inflow and is gradually released back to the atmosphere over time through decay. Detailed parameterisation and product allocation assumptions are provided in the Supplementary Note 7.

Scenario framework

We define seven scenarios to assess India's long-term land use emissions: (i) Reference (business-as-usual) with no additional climate policies, (ii) FP-2050 (FTC reaching 33% by 2050), (iii) FP-2070 (FTC reaching 33% by 2070), (iv) NZ-FP-2050 (net-zero energy with FP-2050), (v) NZ-FP-2070 (net-zero energy with FP-2070), (vi) NZ-FP-2050-AF (net-zero energy with FP-2050 and agroforestry practices) and (vii) NZ-FP-2070-AF (net-zero energy with FP-2070 and agroforestry practices) (Table 2). By comparing these scenarios and their uncertainty informed variants, we examine how different policy, management, and biophysical assumptions shape India's long-term land-use sequestration trajectories through an integrated modelling framework. Within this framework, externally imposed assumptions such as socio-economic, FTC targets, agroforestry adoption, and net-zero energy constraints interact with endogenous land-use choices and carbon-cycle processes to generate internally consistent system-level pathways. Therefore, the outcomes related to land competition, forest maturity, biomass demand, and long-term sequestration behaviour emerge through interactions within the modelling framework (see Supplementary Note 1 for more details). Importantly, the agroforestry scenarios represent a distinct land-management pathway in India, where rotational harvesting is commonly practiced in agroforestry and TOF systems managed by farmers, while forest lands are primarily managed for conservation with restricted commercial harvesting.

Examining these, we gain insights into the differences in emissions, sequestration rates, and their interactions with agriculture and other sectors of the economy when the forest policy target is achieved by 2050 and 2070, implemented through agroforestry (rotational harvesting) or conservation led forest land expansion.

While the focus of our analysis is land-use change emissions, we constrain energy sector emissions across net-zero scenarios. The key motivation behind constraining energy sector emissions through 2070 and beyond is to simulate bio-energy demand from the land use sector. Bio-energy is one source of low-carbon energy in the suite of decarbonisation

Table 2 | Scenarios for India's long-term land use emission pathways

Scenario	Description	Key Features
Reference	Business-as-usual pathway representing continuation of current socio-economic development, agricultural expansion, and historical land-use trends without introducing additional climate mitigation or afforestation policies beyond existing trajectories.	- No additional climate mitigation policies.- Represents current practices and trends.
FP-2050	FTC enhancement policy scenario based on India's National Forest Policy (1988) target of 33% FTC, achieved by 2050.	- Linear increase in FTC from ~80.9 Mha (2020) to ~108.5 Mha by 2050.- Represents enhanced afforestation efforts.
FP-2070	FTC enhancement policy scenario targeting 33% FTC, achieved by 2070.	- Linear increase in FTC from ~80.9 Mha (2020) to ~108.5 Mha by 2070.- Extended timeline for achieving FTC target compared to FP-2050.
NZ-FP-2050	Integrated net-zero transition pathway combining accelerated FTC expansion (FP-2050) with India's long-term net-zero target by 2070.	- Severe emission constraints in energy related carbon dioxide emissions.- Energy emissions capped at 360 MtCO ₂ by 2070.- Assumes 33% FTC achieved by 2050.
NZ-FP-2070	Integrated net-zero transition pathway combining gradual FTC expansion (FP-2070) with India's 2070 net-zero target.	- Severe emission constraints in energy related carbon dioxide emissions.- Energy emissions capped at 360 MtCO ₂ by 2070.- Assumes 33% FTC achieved by 2070.
NZ-FP-2050-AF	Net-Zero energy scenario combined with FP-2050 and agroforestry practices	- Severe emission constraints in energy related carbon dioxide emissions.- Energy emissions capped at 360 MtCO ₂ by 2070.- Assumes 33% FTC achieved by 2050.- The newly added FTC under this policy have been included in the agroforestry system with 5, 15- and 30-years rotation periods divided equally in the additional FTC area.
NZ-FP-2070-AF	Net-Zero energy scenario combined with FP-2070 and agroforestry practices	- Severe emission constraints in energy related carbon dioxide emissions.- Energy emissions capped at 360 MtCO ₂ by 2070.- Assumes 33% FTC achieved by 2070.- The newly added FTC under this policy have been included in the agroforestry system with 5, 15- and 30-years rotation periods divided equally in the additional FTC area.

India's National Forest Policy (1988) specifies a target of bringing 33% of the country's geographical area under FTC, but does not prescribe a timeline for achieving this target. Therefore, this study explores both an accelerated implementation pathway (2050) and a gradual implementation pathway aligned with India's net-zero target year (2070) to evaluate how the timing of FTC expansion influences long-term sequestration dynamics and land-use transitions.

options. The important part to emphasise here is that bioenergy demand has a strong link to land use transition. We expect that under a net-zero scenario, transitions in India's energy sector will lead to higher bioenergy demand and consequently some impact on land use behaviour and associated emissions^{20,115}. The constraint on energy sector emissions in our assessment is solely to capture this critical linkage. The choice of numerical value of the constraint is only to the extent that it can simulate bioenergy demand and its land use implication. The energy-sector CO₂ constraint affects bioenergy deployment through energy demand, but it does not prescribe or cap land-use sequestration, which is resolved independently within the land system⁹⁵.

As there is no right or wrong number for this constraint intended to simulate bioenergy demand, we chose a number that reflected current emissions sequestration. We allow the energy sector to emit 360 MtCO₂ in 2070, which reflects the last 10 years average sequestration by Indian LULUCF sector⁸. To be sure, the 360 MtCO₂ limit in 2070 is small compared to India's current annual energy sector carbon dioxide emissions of around 2500 MtCO₂ which are expected to grow significantly at least till 2040 due to development concerns. Importantly, this choice has no material implications for our results. We explicitly tested both a lower bound (250 MtCO₂) and a high-end bound (1000 MtCO₂) for residual energy-sector emissions to assess their implications for long-term land-use and emissions outcomes in GCAM. Across this wide range, biomass area in 2070 varies only marginally, indicating a very limited land-use response. Consistent with this, total land-sector sequestration and emissions outcomes in 2070 show only modest sensitivity to assumption related to energy sector emissions constraint: across scenarios, sequestration values in 2070 increase by only ~0.3 MtCO₂ when moving from 250 to 360 MtCO₂ constraint, and by ~7 MtCO₂ when moving from 360 to 1000 MtCO₂ constraint, a marginal change relative to total land-sector sequestration levels of in 2070 as presented in our Results. These differences are small in absolute terms and do not alter land-use mitigation outcomes or their ordering across scenarios, indicating that land-use results are not driven by this assumption.

Notably, bioenergy plays an important role in the net-zero energy scenarios as part of the energy system's endogenous response to the imposed CO₂ constraint. In GCAM, biomass supply comprises purpose-grown biomass crops, agricultural residues, and municipal solid waste, with land requirements for biomass crops and residues accounted for within the cropland land-use category⁹⁴. Hence, the deployment of bioenergy technologies, including biomass with carbon capture and storage (BECCS), is determined endogenously based on relative costs, resource availability, and the energy-sector emissions constraint. As a result, negative emissions associated with biomass

arise from CO₂ capture and storage during energy conversion and are treated as energy-sector removals rather than land-based sequestration. It should be noted here that in all scenarios, climate change pathways are not prescribed exogenously through Representative Concentration Pathways, nor are climate-driven impacts on land productivity or carbon sequestration explicitly modelled. Instead, climate outcomes emerge endogenously from the integrated assessment framework based on the assumed socio-economic trajectories, energy-sector transitions, and land-use policies.

Data sources

It is critical to contextualise the model to Indian conditions to ensure that the results and insights are policy relevant. We make significant updates to the model by reflecting India-specific assumptions based on India-specific data sources pertaining to the following:

- Socio-economic parameters: This includes historical and future socio-economic data, such as population, GDP, and per capita income.
- Land-use area: This includes area under land-use for different land categories related to forest, grassland, cropland (net-sown area), habitation, other arable land (same as agricultural fallow land), shrubland, and other land categories.
- Terrestrial carbon: This includes current status of carbon density as well as carbon density values associated with maturity stage of soil and biomass carbon across various land-use categories.
- Forest categorization and management assumptions: This includes assumptions related to the status of management of forest lands, i.e., if human interventions and practices are allowed within forest lands to achieve production, ecological, or social functions.

Details related to India-specific data sources for each of the four aspects mentioned above have been provided in Table 3.

Sensitivity analysis of carbon density values

There are several key parameters related to forests and croplands that significantly influence the model's output, including vegetation and soil carbon density, as well as maturity age. To better understand the variation in these parameters and their implications for the model's output, we conducted a sensitivity analysis by adjusting these key parameters derived from the literature and available datasets. The design of the sensitivity experiments and underlying assumptions are presented in Supplementary Note 3 and 4. We perform sensitivity analysis related to only forest and cropland categories, given their outsized influence on India's land-use emissions profile. For

Table 3 | Data sources and key inputs used in this study

Variables	Description	Data Source
Population	We have used comprehensive decadal Census of India data, which provided past data plus projections up to 2035. For projections beyond that timeframe, we have incorporated data from the United Nations population projections (Supplementary Fig. 1).	116,117
Economic factors	Economic factors such as Gross domestic product (GDP) projections have been provided by NITI Aayog (Supplementary Fig. 1).	118
Land Use Land Cover	We referred to detailed reports from the Forest Survey of India for Forest and Tree Cover. Similarly, data on harvested areas for cropland were sourced from the Land Use Statistics of the Government of India. Other land use categories were derived from the National Remote Sensing Centre (NRSC) (Supplementary Table 6).	68,119–127
Vegetation and soil carbon density	Vegetation and soil carbon density are essential variables in calculating the sequestration potential across different land categories. We obtained carbon density datasets from India's national forest survey agency. However, to analyse the sensitivity of the results we also collected carbon density values from a widespread literature review ($N = 45$), along with GCAM model default ¹²⁸ . To fairly represent this uncertainty range, two explicit scenarios of carbon densities are modelled in this manuscript one is FSI figures representing the lower end of the values and the second one is GCAM model default representing the higher end of the literature-reported global carbon density (GCD) values (Supplementary Table 3, 4 and 7).	68,128
Agriculture yield	To account for agricultural yield growth, projections provided by the Food and Agricultural Organization (FAO) for were used. We relied on model default sources for other economic, water, and agricultural-related data due to their strong alignment with India-specific data, ensuring a robust foundation for our analysis.	129
Energy	To explore the potential of the land use sector in achieving India's short-term NDC and long-term net-zero targets, we also calibrated the energy sector by considering India-specific datasets.	20

clarity of presentation, alternative carbon density assumptions are grouped into three representative cases—Low, Medium, and High—corresponding to lower-bound, central, and upper-bound values within the assumed uncertainty range (Supplementary Note 5 and Supplementary Table 9). The Low case reflects conservative assumptions with lower cropland SOC sequestration potential and forest carbon densities based primarily on India-specific observations. The Medium case represents a balanced central estimate, combining moderate cropland SOC potential with forest carbon densities averaged between India-specific and global values. The High case reflects an upper-bound potential, combining higher cropland SOC equilibrium with forest carbon densities derived from global datasets. This categorisation allows the results to be interpreted as uncertainty envelopes around land-sector sequestration outcomes, rather than as distinct policy scenarios. Unless otherwise stated, results presented in the main text assume a cropland SOC maturation timescale of 50 years. Alternative assumptions regarding cropland SOC maturation (e.g., 100 years) and forest vegetation maturation are explored separately in the Supplementary Materials (Supplementary Note 3 and 4). Forest soil carbon maturation is not varied in the sensitivity analysis because SOC turnover times in forest systems are substantially longer²⁵ than the modelled time horizon, and changes over the study period are therefore limited.

Diagnostic assessment of modelled base-year against national inventories emissions

As a diagnostic check on the robustness of the modelling framework and emissions accounting, we conducted a systematic comparison of modelled base-year (2015) land-use emissions with India's official national inventory reported in the TNC-IAC⁹⁸. This is intended to evaluate consistency in land-use emission patterns and to identify differences arising from accounting definitions, land-category mappings, and data coverage.

The comparison explicitly accounts for structural differences between the modelling framework and the national inventory. In particular, national inventory reporting distinguishes sequestration occurring within designated forest areas from that associated with TOFs, whereas the model aggregates sequestration from all tree-covered areas under a unified FTC category. Similar definitional and data-related differences exist for cropland and grassland categories, where national inventory estimates are influenced by limited observational data⁹⁸ and differing treatment of soil carbon fluxes. Quantitative differences between modelled estimates and inventory values, along with their interpretation for forest, cropland, and grassland categories, are presented and discussed in the Supplementary Note 6.

Data availability

All datasets used in this study (Table 3 and Supplementary Table 6) are publicly available and can be downloaded from the respective sources. The datasets generated and analysed in this study are openly available in a public Zenodo repository at <https://doi.org/10.5281/zenodo.21853095>. These data comprise the numerical source data underlying all main and Supplementary Figures (CSV and XLSX), the GCAM input datasets specific to this study (XML and CSV), the geospatial soil organic carbon raster layers (GeoTIFF), and the outputs from the GCAM model and add-on modules. A file-by-file mapping of each figure to its source-data file is provided in the repository. There are no restrictions on data access; any queries regarding the data can be directed to the corresponding author, V. Chaturvedi (vaibhav.chaturvedi@ceew.in) or first author, J. Rajbanshi (joy.rajbanshi@ceew.in).

Code availability

GCAM is an open-source community model available at <https://github.com/JGCRI/gcam-core/releases>. The additional GCAM data-system codes, the two add-on modules developed in this study (the agroforestry harvested wood products sequestration module and the cropland soil emission module), and all scripts used to generate the figures are openly available at <https://github.com/joyrajbanshi91/India-Land-Use>

Received: 28 October 2025; Accepted: 27 August 2026;

References

- Nunez, S., Arets, E., Alkemade, R., Verwer, C. & Leemans, R. Assessing the impacts of climate change on biodiversity: is below 2 °C enough? *Clim. Change* **154**, 351–365 <https://doi.org/10.1007/s10584-019-02420-x> (2019).
- Raimondo, M., Nazzaro, C., Marotta, G. & Caracciolo, F. Land degradation and climate change: global impact on wheat yields. *Land Degrad. Dev.* **32**, 387–398 <https://doi.org/10.1002/ldr.3699> (2021).
- Rajbanshi, J. & Das, S. The variability and teleconnections of meteorological drought in the Indian summer monsoon season: implications for staple crop production. *J. Hydrol.* **603**, 126845 <https://doi.org/10.1016/j.jhydrol.2021.126845> (2021).
- UNFCCC. GHG Data from UNFCCC. *United Nations Framework Convention on Climate Change (n.d.)*. (accessed 20 October 2024) <https://unfccc.int/topics/mitigation/resources/registry-and-data/ghg-data-from-unfccc>.
- Keenan, T. F. & Williams, C. A. The terrestrial carbon sink. *Annu. Rev. Environ. Resour.* **43**, 219–243 <https://doi.org/10.1146/annurev-environ-102017-030204> (2018).
- Zhu, K., Song, Y. & Qin, C. Forest age improves understanding of the global carbon sink. *Proc. Natl. Acad. Sci. USA* **116**, 3962–3964 <https://doi.org/10.1073/pnas.1900797116> (2019).
- Nabuurs, G.-J. et al. Agriculture, forestry and other land uses (AFOLU). In *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* <https://doi.org/10.1017/9781009157926.009> (Cambridge University Press, 2022).
- MoEFCC. India: Third Biennial Update Report to the United Nations Framework Convention on Climate Change <https://unfccc.int/documents/268470> (Government of India Ministry of Environment, Forest and Climate Change, 2021).
- Ministry of Environment and Forests. *National Forest Policy, 1988* (Government of India, 1988).
- Singh, R. K., Sinha, V. S. P., Joshi, P. K. & Kumar, M. Modelling agriculture, forestry and other land use (AFOLU) in response to climate change scenarios for the SAARC nations. *Environ. Monit. Assess.* **192**, 4 <https://doi.org/10.1007/s10661-020-8144-2> (2020).
- Jha, C. K. et al. Pathway to achieve a sustainable food and land-use transition in India. *Sustain. Sci.* **18**, 457–468 <https://doi.org/10.1007/s11625-022-01193-0> (2023).
- UNDP. *The SDGs in Action: What are the Sustainable Development Goals?* <https://www.undp.org/sustainable-development-goals> (United Nations Development Programme, 2023).
- Ravindranath, N. H., Murthy, I. K., Chaturvedi, R. K., Andrasko, K. & Sathaye, J. A. Carbon forestry economic mitigation potential in India, by land classification. *Mitig. Adapt. Strateg. Glob. Change* **12**, 1027–1050 <https://doi.org/10.1007/s11027-006-9063-4> (2007).
- Chaturvedi, R. K., Gopalakrishnan, R., Sukumar, R. & Ravindranath, N. H. Carbon management in Indian forests: a policy analysis to assess mitigation potential. *Carbon Manag.* **1**, 109–117 <https://doi.org/10.4155/cmt.10.19> (2010).
- Gopalakrishna, T. et al. Existing land uses constrain climate change mitigation potential of forest restoration in India. *Conserv. Lett.* **15**, 1–11 <https://doi.org/10.1111/conl.12867> (2022).
- Jha, C. K. et al. The role of food and land use systems in achieving India's sustainability targets. *Environ. Res. Lett.* **17**, 074022 <https://doi.org/10.1088/1748-9326/ac788a> (2022).
- Hinz, R. et al. Agricultural development and land use change in India: a scenario analysis of trade-offs between UN Sustainable

- Development Goals (SDGs). *Earth's Future* **8**, 0–3 <https://doi.org/10.1029/2019EF001287> (2020).
18. Chaturvedi, V., Eom, J., Clarke, L. E. & Shukla, P. R. Long-term building energy demand for India: disaggregating end-use energy services in an integrated assessment modeling framework. *Energy Policy* **64**, 226–242 <https://doi.org/10.1016/j.enpol.2012.11.021> (2014).
 19. la Rue du Can, S. et al. Modeling India's energy future using a bottom-up approach. *Appl. Energy* **238**, 1108–1125 <https://doi.org/10.1016/j.apenergy.2019.01.065> (2019).
 20. Chaturvedi, V. & Malyan, A. Implications of a net-zero target for India's sectoral energy transitions and climate policy. *Oxford Open Climate Change* **2**, 1–15 <https://doi.org/10.1093/oxfclm/kgac001> (2022).
 21. Chiquier, S., Gurgel, A., Morris, J., Chen, Y.-H. H. & Paltsev, S. Integrated assessment of carbon dioxide removal portfolios: land, energy, and economic trade-offs for climate policy. *Environ. Res. Lett.* **20**, 024002 <https://doi.org/10.1088/1748-9326/ada4c0> (2025).
 22. Ampah, J. D. et al. Deployment expectations of multi-gigatonne scale carbon removal could have adverse impacts on Asia's energy–water–land nexus. *Nat. Commun.* **15**, 6342 <https://doi.org/10.1038/s41467-024-50594-5> (2024).
 23. Afrane, S. et al. Targeted carbon dioxide removal measures are essential for the cost and energy transformation of the electricity sector by 2050. *Commun. Earth Environ.* **6**, 227 <https://doi.org/10.1038/s43247-025-02190-8> (2025).
 24. Ogungbemi, A. T. & Dagbasi, M. The role of carbon removal in ratcheting India's net-zero goal. *Sustainability* **17**, 5632 <https://doi.org/10.3390/su17125632> (2025).
 25. Naitam, R. & Bhattacharyya, T. Quasi-equilibrium of organic carbon in shrink–swell soils of the subhumid tropics in India under forest, horticulture, and agricultural systems. *Aust. J. Soil Res.* **42**, 181–188 (2004).
 26. Narayan, P. K. & Narayan, S. Carbon dioxide emissions and economic growth: panel data evidence from developing countries. *Energy Policy* **38**, 661–666 (2010).
 27. Paliwal, U., Sharma, M. & Burkhart, J. F. Monthly and spatially resolved black carbon emission inventory of India: uncertainty analysis. *Atmos. Chem. Phys.* **16**, 12457–12476 (2016).
 28. Giest, S. Big data analytics for mitigating carbon emissions in smart cities: opportunities and challenges. *Eur. Plan. Stud.* **25**, 941–957 (2017).
 29. Depoers, F., Jeanjean, T. & Jérôme, T. Voluntary disclosure of greenhouse gas emissions: contrasting the carbon disclosure project and corporate reports. *J. Bus. Ethics* **134**, 445–461 (2016).
 30. Shan, Y., Huang, Q., Guan, D. & Hubacek, K. China CO₂ emission accounts 2016–2017. *Sci. Data* **7**, 1–9 (2020).
 31. Pal, D. K., Wani, S. P. & Sahrawat, K. L. Carbon sequestration in indian soils: present status and the potential. *Proc. Natl. Acad. Sci. India Sect. B-Biol. Sci.* **85**, 337–358 (2015).
 32. Mohanty, M. et al. Soil carbon sequestration potential in a Vertisol in central India- results from a 43-year long-term experiment and APSIM modeling. *Agric. Syst.* **184**, 102906 (2020).
 33. Weyant, J. et al. Integrated assessment of climate change: an overview and comparison of approaches and results. *Climate Change 1995: Economic and Social Dimensions of Climate Change, Working Group III Second Assessment Report of the IPCC*, 367–396 (Cambridge University Press, 1995) https://www.researchgate.net/publication/221678860_Integrated_Assessment_of_Climate_Change_An_Overview_and_Comparison_of_Approaches_and_Results.
 34. Fischer, G., Shah, M., Tubiello, F. N. & Van Velhuizen, H. Socio-economic and climate change impacts on agriculture: an integrated assessment, 1990–2080. *Philos. Trans. R. Soc. B Biol. Sci.* **360**, 2067–2083 <https://doi.org/10.1098/rstb.2005.1744> (2005).
 35. Howells, M. et al. Integrated analysis of climate change, land-use, energy and water strategies. *Nat. Clim. Change* **3**, 621–626 <https://doi.org/10.1038/nclimate1789> (2013).
 36. IPCC-IPBES. *Biodiversity and Climate Change: Scientific Outcome* https://ipbes.net/sites/default/files/2021-06/2021_IPCC-IPBES_scientific_outcome_20210612.pdf (IPBES-IPCC Co-Sponsored Workshop, 2020).
 37. Chaturvedi, V. & Shukla, P. R. Role of energy efficiency in climate change mitigation policy for India: assessment of co-benefits and opportunities within an integrated assessment modeling framework. *Climatic Change* **123**, 597–609 <https://doi.org/10.1007/s10584-013-0898-x> (2014).
 38. Shi, W. et al. Projecting state-level air pollutant emissions using an integrated assessment model: GCAM-USA. *Appl. Energy* **208**, 511–521 <https://doi.org/10.1016/j.apenergy.2017.09.122> (2017).
 39. PIB. *Year End Review: Ministry of Environment Forest and Climate Change* 23 <https://pib.gov.in/PressReleasePage.aspx?PRID=1886051> (Press Information Bureau, Ministry of Environment, Forest and Climate Change, 2022).
 40. Terakunpisut, J., Gajasen, N. & Ruankawe, N. Carbon sequestration potential in aboveground biomass of Thong Pha Phum National Forest, Thailand. *Appl. Ecol. Environ. Res.* **5**, 93–102 https://doi.org/10.15666/aer/0502_093102 (2007).
 41. Wu, T. et al. Carbon sequestration by fruit trees: Chinese apple orchards as an example. *PLoS ONE* **7**, 1–13 <https://doi.org/10.1371/journal.pone.0038883> (2012).
 42. Yao, Y., Piao, S. & Wang, T. Future biomass carbon sequestration capacity of Chinese forests. *Sci. Bull.* **63**, 1108–1117 <https://doi.org/10.1016/j.scib.2018.07.015> (2018).
 43. Zhou, T. et al. Age-dependent forest carbon sink: estimation via inverse modelling. *J. Geophys. Res. Biogeosci.* **120**, 2473–2492 <https://doi.org/10.1002/2015JG002943> (2015).
 44. Sommer, R. & Bossio, D. Dynamics and climate change mitigation potential of soil organic carbon sequestration. *J. Environ. Manag.* **144**, 83–87 <https://doi.org/10.1016/j.jenvman.2014.05.017> (2014).
 45. Lal, R. Soil carbon sequestration impacts on global climate change and food security. *Science* **304**, 1623–1627 <https://doi.org/10.1126/science.1097396> (2004).
 46. Bhattacharyya, T., Chandran, P., Ray, S. K., Mandal, C., Tiwary, P., Pal, D. K., Wani, S. P. & Sahrawat, K. L. Processes determining the sequestration and maintenance of carbon in soils: a synthesis of research from tropical India. *Soil Horiz.* **55**, 1–16 <https://doi.org/10.2136/sh14-01-0001> (2014).
 47. IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. **4**, Ch. 12. Harvested Wood Products <https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html> (Intergovernmental Panel on Climate Change, 2006).
 48. IPCC. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. **4**, Ch. 12. Harvested Wood Products <https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html> (Intergovernmental Panel on Climate Change, 2019).
 49. Wang, M. et al. Can wood harvest followed by forest regrowth enhance carbon sequestration of the forest sector in China? *Glob. Planet. Change* **243**, 104626 <https://doi.org/10.1016/j.gloplacha.2024.104626> (2024).
 50. Ovando, P. et al. From forest to building: enhancing the use of lower grade wood for climate-responsive construction. *Trees For. People* **22**, 101022 <https://doi.org/10.1016/j.tfp.2025.101022> (2025).
 51. Lippke, B. et al. Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. *Carbon Manag* **2**, 303–333 <https://doi.org/10.4155/cmt.11.24> (2011).
 52. Perez-Garcia, J., Lippke, B., Cornnick, J. & Manriquez, C. An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results. *Wood Fiber Sci.* **37**,

- 140–148 <https://wfs.swst.org/index.php/wfs/article/view/840> (2005).
53. Liu, Y. et al. Contrasting suitability and ambition in regional carbon mitigation. *Nat. Commun.* **13**, 4077 <https://doi.org/10.1038/s41467-022-31729-y> (2022).
54. Friedlingstein, P. et al. Global carbon budget 2024. *Earth Syst. Sci. Data* **17**, 965–1039 <https://doi.org/10.5194/essd-17-965-2025> (2025).
55. Carton, W., Lund, J. F. & Dooley, K. Undoing equivalence: rethinking carbon accounting for just carbon removal. *Front. Clim.* **3**, 664130 <https://doi.org/10.3389/fclim.2021.664130> (2021).
56. Harmsen, M. et al. Uncertainty in non-CO₂ greenhouse gas mitigation contributes to ambiguity in global climate policy feasibility. *Nat Commun* **14**, 2949 <https://doi.org/10.1038/s41467-023-38577-4> (2023).
57. Lund, J. F., Markusson, N., Carton, W. & Buck, H. J. Net zero and the unexplored politics of residual emissions. *Energy Res. Soc. Sci.* **98** 103035 <https://doi.org/10.1016/j.erss.2023.103035> (2023).
58. Jose, S. Agroforestry for ecosystem services and environmental benefits: an overview. *Agrofor. Syst.* **76**, 1–10 <https://doi.org/10.1007/s10457-009-9229-7> (2009).
59. Chavan, S. B. et al. National agroforestry policy in India: a low hanging fruit. *Curr. Sci.* **108**, 1826–1834 (2015).
60. Visscher, A. M. et al. Agroforestry enhances biological activity, diversity and soil-based ecosystem functions in mountain agroecosystems of Latin America: a meta-analysis. *Glob. Change Biol.* **30**, e17036 <https://doi.org/10.1111/gcb.17036> (2024).
61. IPCC. *Global Warming of 1.5 °C: An IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* (eds. Masson-Delmotte, V. et al.) <https://doi.org/10.1017/9781009157940> (Cambridge Univ. Press, 2018).
62. Ministry of Environment, Forest and Climate Change (MoEFCC). *National Mission for a Green India: Revised Mission Document* <https://moef.gov.in/uploads/2017/08/Revised%20Mission%20Document.pdf> (Government of India, New Delhi, 2021).
63. NITI Aayog. *Greening and Restoration of Wastelands with Agroforestry* (G.R.O.W.) <https://niti.gov.in/sites/default/files/2024-02/Grow%20Report%2020.02.2024.pdf> (Government of India, 2024).
64. Telangana Government. *Telanganaku Haritha Haram* (accessed 7 August 2026) <https://hyderabad.telangana.gov.in/scheme/haritha-haram/> (Government of Telangana).
65. Tamil Nadu Green Climate Company. *Green Tamil Nadu Mission: Mission Document* https://www.tngcc.tn.gov.in/wp-content/uploads/2025/12/GTM_Document.pdf (Government of Tamil Nadu).
66. Sanyal, S., Shinghal, K. & Bali, N. *Agroforestry: Missing Trees for the Forest*. EAC-PM Working Paper EAC-PM/WP/32/2024 <https://eacpm.gov.in/wp-content/uploads/2024/09/Working-Pap-r-on-Agroforestry.pdf> (Economic Advisory Council to the Prime Minister, 2024).
67. Houghton, R. A., Hackler, J. L. & Lawrence, K. T. The U.S. carbon budget: contributions from land-use change. *Science* **285**, 574–578 <https://www.cr.usgs.gov/landdaac/glcc/glcc.html> (1999).
68. FSI. *India State Forest Report 2021* (Forest Survey of India, 2021).
69. Luo, Y. et al. Toward more realistic projections of soil carbon dynamics by Earth system models. *Glob. Biogeochem. Cycles* **30**, 40–56 <https://doi.org/10.1002/2015GB005239> (2016).
70. Minasny, B. et al. Soil carbon 4 per mille. *Geoderma* **292**, 59–86 <https://doi.org/10.1016/j.geoderma.2017.01.002> (2017).
71. Ogle, S. M. et al. Counterfactual scenarios reveal historical impact of cropland management on soil organic carbon stocks in the United States. *Sci. Rep.* **13**, 1–13 <https://doi.org/10.1038/s41598-023-41307-x> (2023).
72. Poulton, P. et al. Major limitations to achieving ‘4 per 1000’ increases in soil organic carbon stock in temperate regions: evidence from long-term experiments at Rothamsted Research, UK. *Int. J. Lab. Hematol.* **38**, 42–49 <https://doi.org/10.1111/ijlh.12426> (2018).
73. Madhusudan, M. D. & Vanak, A. T. Mapping the distribution and extent of India’s semi-arid open natural ecosystems. *J. Biogeogr.* **50**, 1377–1387 <https://doi.org/10.1111/jbi.14471> (2022).
74. PIB. *Protection and Preservation of Wetlands 18*. <https://pib.gov.in/PressReleasePage.aspx?PRID=1842626> (Press Information Bureau, Ministry of Environment, Forest and Climate Change, 2022).
75. Desai, A. R., Bolstad, P. V., Cook, B. D., Davis, K. J. & Carey, E. V. Comparing net ecosystem exchange of carbon dioxide between an old-growth and mature forest in the upper Midwest. *USA. Agric. For. Meteorol.* **128**, 33–55 (2005).
76. Zhou, G. et al. Old-growth forests can accumulate carbon in soils. *Science* **314**, 1417 (2006).
77. Luyssaert, S. et al. Old-growth forests as global carbon sinks. *Nature* **455**, 213–215 (2008).
78. Keenan, T. F. et al. Net carbon uptake has increased through warming-induced changes in temperate forest phenology. *Nat. Clim. Chang.* **4**, 598–604 (2014).
79. Pregitzer, K. S. & Euskirchen, E. S. Carbon cycling and storage in world forests: biome patterns related to forest age. *Glob. Chang. Biol.* **10**, 2052–2077 (2004).
80. Phillips, O. L. et al. Increasing dominance of large lianas in Amazonian forests. *Nature* **418**, 770–774 (2002).
81. Norby, R. J. et al. Forest response to elevated CO₂ is conserved across a broad range of productivity. *Proc. Natl. Acad. Sci. USA*. **102**, 18052–18056 (2005).
82. Magnani, F. et al. The human footprint in the carbon cycle of temperate and boreal forests. *Nature* **447**, 848–850 (2007).
83. Pereira, J. S. et al. Net ecosystem carbon exchange in three contrasting Mediterranean ecosystems -The effect of drought. *Biogeosciences* **4**, 791–802 (2007).
84. Liu, J. et al. Contrasting carbon cycle responses of the tropical continents to the 2015–2016 El Niño. *Science* **358** <https://doi.org/10.1126/science.aam5690> (2017).
85. Martí-Roura, M., Casals, P. & Romanyà, J. Temporal changes in soil organic C under Mediterranean shrublands and grasslands: impact of fire and drought. *Plant Soil* **338**, 289–300 <https://doi.org/10.1007/s11104-010-0485-0> (2011).
86. IPCC. *Climate Change 2022: Mitigation of Climate Change – Frequently Asked Questions (FAQs), Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FAQs_Compiled.pdf (IPCC, 2022).
87. Roe, S. et al. Land-based measures to mitigate climate change: potential and feasibility by country. *Glob. Change Biol.* **27**, 6025–6058 <https://doi.org/10.1111/gcb.15873> (2021).
88. Fuss, S. et al. Negative emissions—Part 2: costs, potentials and side effects. *Environ. Res. Lett.* **13**, 063002 <https://doi.org/10.1088/1748-9326/aabf9f> (2018).
89. Roman-Cuesta, R. M. et al. Land remains a blind spot in tracking progress under the Paris Agreement due to lack of data comparability. *Commun Earth Environ* **6**, 598 <https://doi.org/10.1038/s43247-025-02494-9> (2025).
90. Doelman, J. C. et al. Afforestation for climate change mitigation: potentials, risks and trade-offs. *Glob. Change Biol.* **26**, 1576–1591 <https://doi.org/10.1111/gcb.14887> (2020).
91. Grassi, G. et al. Critical adjustment of land mitigation pathways for assessing countries’ climate progress. *Nat. Clim. Change* **11**, 425–434 <https://doi.org/10.1038/s41558-021-01033-6> (2021).

92. Robinson, N. & Benke, K. Analysis of uncertainty in the depth profile of soil organic carbon. *Environments* **10**, 29 <https://doi.org/10.3390/environments10020029> (2023).
93. Spawn, S. A., Lark, T. J. & Gibbs, H. K. Carbon emissions from cropland expansion in the United States. *Environ. Res. Lett.* **14** <https://doi.org/10.1088/1748-9326/ab0399> (2019).
94. Calvin, K. et al. GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems. *Geosci. Model Dev.* **12**, 677–698 <https://doi.org/10.5194/gmd-12-677-2019> (2019).
95. Guivarch, C. & Rogelj, J. Carbon price variations in 2 °C scenarios explored. In *Carbon Pricing Leadership Coalition (CPLC)* 15 <https://pure.iiasa.ac.at/id/eprint/14685/> (2017).
96. Edelenbosch, O. Y., van Vuuren, D. P., Blok, K., Calvin, K. & Fujimori, S. Mitigating energy demand sector emissions: the integrated modelling perspective. *Appl. Energy* **261**, 114347 <https://doi.org/10.1016/j.apenergy.2019.114347> (2019).
97. Kyle, P., McFarland, J. D. & Melillo, J. A. *GCAM 3.0 Agriculture and Land Use: Data Sources and Methods* https://www.researchgate.net/publication/255250831_GCAM_30_Agriculture_and_Land_Use_Data_Sources_and_Methods (Pacific Northwest National Laboratory, 2011).
98. India. *National Communication (NC)*. NC 3 <https://unfccc.int/documents/636235> (Government of India, 2023).
99. Coleman, K. et al. Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. *Geoderma* **81**, 29–44 [https://doi.org/10.1016/S0016-7061\(97\)00079-7](https://doi.org/10.1016/S0016-7061(97)00079-7) (1997).
100. Parton, W. J. The CENTURY model. In *Evaluation of Soil Organic Matter Models* (eds. Powelson, D. S. et al.) 283–291 (Springer, 1996).
101. Zhang, Q., Huang, R., Wu, W. & Liu, X. Estimating soil organic carbon at equilibrium using a logistic model. *Commun. Soil Sci. Plant Anal.* **39**, 627–640 <https://doi.org/10.1080/00103620701879000> (2008).
102. Zomer, R. J., Bossio, D. A., Sommer, R. & Verchot, L. V. Global sequestration potential of increased organic carbon in cropland soils. *Sci. Rep.* **7**, 15554 <https://doi.org/10.1038/s41598-017-15794-8> (2017).
103. Poeplau, C. et al. Temporal dynamics of soil organic carbon after land-use change in the temperate zone – carbon response functions as a model approach. *Glob. Change Biol.* **17**, 2415–2427 <https://doi.org/10.1111/j.1365-2486.2011.02408.x> (2011).
104. Lal, R. Soil carbon management and climate change. *Carbon Manag* **4**, 439–462 <https://doi.org/10.4155/cmt.13.31> (2013).
105. Sreenivas, K. et al. Digital mapping of soil organic and inorganic carbon status in India. *Geoderma* **269**, 160–173 (2016).
106. Hengl, T. et al. SoilGrids250m: global gridded soil information based on machine learning. *PLoS ONE* **12**, e0169748 <https://doi.org/10.1371/journal.pone.0169748> (2017).
107. Padarian, J., Minasny, B., McBratney, A. & Smith, P. Soil carbon sequestration potential in global croplands. *PeerJ* **10**, e13740 <https://doi.org/10.7717/peerj.13740> (2022).
108. Chiról, C., Séré, G., Redon, P.-O., Chenu, C. & Derrien, D. Depth dependence of soil organic carbon additional storage capacity in different soil types by the 2050 target for carbon neutrality. *Soil* **11**, 149–174 <https://doi.org/10.5194/soil-11-149-2025> (2025).
109. Dhyani, S. K. & Handa, A. K. & Uma. Area under agroforestry in India: an assessment for present status and estimation of potential. *Indian J. Agrofor.* **15**, 1–11 (2013).
110. Nath, A. J. et al. Agroforestry land suitability analysis in the Eastern Indian Himalayan region. *Environ. Challenges* **4**, 100199 (2021).
111. Datta, P., Behera, B. & Rahut, D. B. India's approach to agroforestry as an effective strategy in the context of climate change: an evaluation of 28 state climate change action plans. *Agric. Syst.* **214**, 103840 (2024).
112. Hou, G., Delang, C. O., Lu, X. & Olschewski, R. Optimizing rotation periods of forest plantations: the effects of carbon accounting regimes. *Forest Policy Econ.* **118**, 102263 <https://doi.org/10.1016/j.forpol.2020.102263> (2020).
113. Chaturvedi, O. P. et al. Promising agroforestry tree species in India <https://www.cifor-icraf.org/publications/downloads/Publications/PDFS/B17969.pdf> (Central Agroforestry Research Institute (CAFRI) & World Agroforestry Centre (ICRAF), 2017).
114. Richards, F. J. A flexible growth function for empirical use. *J. Exp. Bot.* **10**, 290–301 <https://doi.org/10.1093/jxb/10.2.290> (1959).
115. Das, P. et al. A new scenario set for informing pathways to India's next nationally determined contribution and 2070 net-zero target: structural reforms, LIFE, and sectoral pathways. *Energy Clim. Change* **6**, 100192 <https://doi.org/10.1016/j.egycc.2025.100192> (2025).
116. Census of India. *Provisional Population Total Paper 2*. <https://censusindia.gov.in/census.website/data/population-finder> (Office of the Registrar General & Census Commissioner, India, 2011).
117. United Nations, Department of Economic and Social Affairs, Population Division. *World Population Prospects 2019: Data Booklet*. ST/ESA/SER.A/424 (2019).
118. NITI Aayog. *India's GDP Projections*. <https://niti.gov.in> (NITI Aayog, 2020).
119. FSI. *India State Forest Report 2005* (Forest Survey of India, 2005).
120. FSI. *India State Forest Report 2009* (Forest Survey of India, 2009).
121. FSI. *India State Forest Report 2011* (Forest Survey of India, 2011).
122. FSI. *India State Forest Report 2013* (Forest Survey of India, 2013).
123. FSI. *India State Forest Report 2015* (Forest Survey of India, 2015).
124. FSI. *India State Forest Report 2017* (Forest Survey of India, 2017).
125. FSI. *India State Forest Report 2019* (Forest Survey of India, 2019).
126. Directorate of Economics and Statistics (DES), Ministry of Agriculture & Farmers Welfare, Government of India. *Land Use Statistics (2000–2005)* https://eands.dacnet.nic.in/LUS_2000_2005.htm.
127. National Remote Sensing Centre (NRSC), Indian Space Research Organisation (ISRO). *Bhuvan Thematic Services Portal* <https://bhuvan-app1.nrsc.gov.in/thematic/thematic/index.php>.
128. Houghton, R. A. The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. *Tellus, Ser. B Chem. Phys. Meteorol.* **51**, 298–313 (1999).
129. Alexandratos, N. & Bruinsma, J. *World Agriculture Towards 2030/2050: The 2012 Revision*. ESA Working Paper No. 12-03 <https://doi.org/10.1126/science.abo7429> (FAO, 2012).

Author contributions

Vaibhav Chaturvedi and Joy Rajbanshi co-developed the concept of the study. Joy Rajbanshi conducted the analysis, created the figures, wrote and revised the manuscript. Vaibhav Chaturvedi supervised the project, provided conceptual guidance and revised the manuscript. Rajiv Kumar Chaturvedi and Raman Sukumar provided regular conceptual guidance, feedback and contributed to discussions throughout the development of the manuscript and also revised the paper. Swati Sharma assisted with data collection and supported the preparation of input files for the model simulations.

Funding

This study has not been financially supported through any specific grant.

Competing interests

Dr. Vaibhav Chaturvedi is an Editorial Board Member for Communications (Communications Earth & Environment) but was not involved in the editorial review or peer review, nor in the decision to publish this article. All authors declare no financial or non-financial competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s43247-026-04035-4>.

Correspondence and requests for materials should be addressed to Vaibhav Chaturvedi.

Peer review information *Communications Earth & Environment* thanks Kristine Karstens, Niclas Bentsen and Vartika Singh for their contribution to the peer review of this work. Primary Handling Editors: Nandita Basu. A peer review file is available.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2026