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Climate-smart forestry through innovative wood products and commercial afforestation and reforestation on marginal land

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Abstract

Afforestation and reforestation (AR) on marginal land are nature-based solutions to climate change. There is a gap in understanding the climate mitigation potential of protection and commercial AR with different combinations of forest plantation management and wood utilization pathways. Here, we fill the gap using a dynamic, multi-scale life cycle assessment to estimate one-century greenhouse gas (GHG) mitigation delivered by (both traditional and innovative) commercial and protection AR with different planting density and thinning regimes on marginal land in the southeastern US. We found that innovative commercial AR generally mitigates more GHGs across 100 years (3.73–4.15 Gt CO₂e) through cross-laminated timber (CLT) and biochar than protection AR (3.35–3.69 Gt CO₂e) and commercial AR with traditional lumber production (3.17–3.51 Gt CO₂e), especially in moderately cooler and dryer regions in this study with higher forest carbon yield, soil clay content, and CLT substitution. In a shorter timeframe (≤ 50 years), protection AR is likely to deliver higher GHG mitigation. On average, for the same wood product, low-density plantations without thinning and high-density plantations with thinning mitigate more life cycle GHGs and result in higher carbon stock than low-density with thinning plantations. Commercial AR increases the carbon stock of standing plantations, wood products, and biochar, but the increases have uneven spatial distributions. Georgia (0.38 Gt C), Alabama (0.28 Gt C), and North Carolina (0.13 Gt C) have the largest carbon stock increases that can be prioritized for innovative commercial AR projects on marginal land.

Significance Statement

Afforestation and reforestation (AR) are nature-based solutions to climate change. However, the greenhouse (GHG) mitigation efficacy of protection or commercial AR is under debate. This study develops a dynamic life cycle assessment to quantify the GHG mitigation potential of protection and commercial AR on marginal land in the southeastern US. We found that commercial AR with cross-laminated timber and biochar production generally mitigate more GHGs across 100 years than protection AR and commercial AR with traditional lumber production. Protection AR could mitigate more GHGs in a shorter timeframe (≤ 50 years). These results highlight the role of synergizing protection AR, innovative wood utilization, and strategic forest plantation management in supporting short- and long-term climate change mitigation goals.

Introduction

Intergovernmental Panel on Climate Change (IPCC) highlights afforestation and reforestation (AR) as a critical land-based greenhouse gas (GHG) mitigation strategy to limit global warming to 1.5–2°C above pre-industrial levels (1–3). However, social and economic competition with other land use (e.g., agriculture and pasture) often limit AR implementation, making ‘marginal lands’ promising candidates (4). The definition of ‘marginal land’ differs in studies but generally includes abandoned or degraded agricultural and pasture lands, grassland, shrublands, non-stocked forests, and post-burn landscapes. These lands comprise low fertility and/or steeply-sloped erosion-prone soils, making them incompatible with other land use but suitable for forest re-growth (4–10). Forests can be restored on marginal land for either protection/conservation or industrial purposes that supply timber and raw materials for wood products (4, 11, 12) or bioenergy (5–8). The global wood product demand is growing rapidly (13). Emerging wood products (e.g., mass timber) have the potential to mitigate climate change by replacing carbon-intensive construction materials (e.g., concrete and steel) (14–17). The source of wood is important. Sourcing timber from existing natural forests negatively impacts biodiversity and other ecosystem services. Commercial AR on marginal land is a promising option to supply timber without creating land competition and converting natural forests.

The GHG mitigation potential of commercial and protection AR has been highlighted in the literature (3, 18–25), but their GHG mitigation efficacy has been debated (18, 26, 27). For instance, commercial AR for wood production in tropical regions is less favorable than protection AR for carbon removal (26), but commercial AR in temperate regions show greater GHG mitigation potential (18). GHG mitigation efficacy of AR depends on regional contexts, such as local climate conditions (18, 26), forest plantation management strategies (3, 19, 27–30), tree species (28, 31), and wood product types and their life cycle activities (e.g., manufacture processes, use, substitution benefits, and end-of-life (EOL)) (18, 19, 29, 30). Emerging wood products, such as cross-laminated timber (CLT), have more environmental benefits than traditional lumber due to their longer lifetime and higher material substitution credits (replacing concrete and steel) (14–17). Combining wood products with other nature-based solutions, such as biochar and bioenergy derived from forest plantation residues, shows additional carbon benefits by reducing wildfire hazard and providing renewable energy and carbon storage (19). Recent research on circular economy applications to the forest sector revealed the benefits of utilizing waste woody biomass in enhancing resource efficiency and reducing environmental burdens associated with current practices such as prescribed burning (32).

There is a gap in understanding the role of synergizing different, innovative wood uses from AR and forest plantation management strategies in mitigating climate change. Previous studies have

67 compared protection and commercial forest plantations for traditional wood products (18) or
68 compared different product combinations in existing forests (19). Most life cycle assessment (LCA)
69 studies of innovative wood use, such as CLT (33–35) and biochar (36–40), have focused on
70 process- or product-level understandings, and they used traditional, static methods without
71 considering spatial and temporal factors (e.g., forest growth, climate and soil conditions). Global
72 analyses of mass timber show the GHG mitigation potential of wood use in buildings (16) and their
73 impacts on land use change (41), but high-resolution, spatially explicit understandings of various
74 combinations of wood use and forest plantation management have not been fully explored. Such
75 understandings are critical for region-specific decision-making because of the high spatial
76 heterogeneity of forest carbon pools, e.g., soil organic carbon (SOC), wood products, and the
77 hyperlocal wood markets where the majority of wood harvested is delivered to mills within 100 miles
78 in the southeastern US (42).

79 This study addresses these knowledge gaps by dynamic, multi-scale life cycle assessment (LCA)
80 modeling (Fig. S1) that links process-scale LCA for wood products and biochar with regional-scale
81 modeling of forest ecosystems on an annual basis for 100 years. Spatially explicit climate and soil
82 conditions were modeled for loblolly pine AR (*Pinus taeda* L.) on marginal land in the southeastern
83 US at 1 km resolution, including Virginia (VA), Tennessee (TN), North Carolina (NC), Mississippi
84 (MS), Alabama (AL), Georgia (GA), South Carolina (SC), and Florida (FL). The cradle-to-grave
85 LCA includes GHG emissions of forest operations, manufacturing, EOL, carbon sequestration of
86 forests, and material substitution credits for replacing steel and concrete in the building industry.
87 Emissions from SOC with spatial heterogeneity were simulated in the RothC model (43). Carbon
88 sequestration through forest growth was estimated based on loblolly pine growth in a 25-year
89 rotation using gridded site index data and the 1996 Plantation Management Research Cooperative
90 (PMRC) whole stand growth and yield model (44).

91 Scenario analysis was conducted to compare the life-cycle GHG mitigation potentials between
92 protection and commercial AR and to explore the effects of different synergies between forest
93 plantation management (e.g., plantation density and thinning) and the use of harvested wood (e.g.,
94 traditional lumber, CLT, and biochar) and forest plantation residues (including aboveground parts
95 of snags, aboveground components of removed trees from thinning, and logging residues). Two
96 baselines were established for protection AR without forest plantation management at low (450
97 trees/acre) and high plantation density (900 trees/acre). Nine scenarios were simulated as a
98 combination of three scenarios for different wood and residue uses and three scenarios of varying
99 forest plantation management strategies. This study estimated the carbon stock change as the
100 change from year zero on marginal land where the aboveground and soil carbon stock is assumed

to be zero and current state, respectively. Carbon stock changes were estimated for different locations and years to understand their temporal-spatial distributions.

Results

100-year GHG balances. Fig. 1 shows that for low-density plantations without thinning, Scenario 3 (S3: innovative commercial AR for CLT production with 100% residue removal for biochar production, a conceptual, extreme case) has similar ranges of 100-year GHG mitigation potential with Scenario 2 (S2: innovative commercial AR for CLT production with 50% residue removal for biochar production), both of which likely deliver more GHG mitigations than Scenario 1 (S1: commercial AR for lumber production without plantation residue removal) and baseline (protection AR). The results of S2 and S3 in low-density plantations without thinning are also similar to the results of the same scenarios in high-density plantations; because more CO₂ sequestered by high-density plantations are primarily canceled out by greater emissions from biochar manufacture, and soil and ground surface respiration associated with more biomass generated in high-density plantations (Fig. 1B). On average, high-density baseline protection AR has higher GHG mitigation potential than high-density S1 with thinning, because residues from thinning are left on soil and forest floor, which contributes to GHG emissions through biomass decomposition (Fig. 1B). These GHG emissions are greatly reduced in S2 and S3 as residues are removed for biochar production, resulting in higher average GHG mitigation of S2 and S3 than high-density protection AR (Fig. 1A-B). In shorter timeframes (e.g., 50 years in Fig. 1), protection AR mitigates more GHG than commercial AR, which can be explained by fast forest growth in early years and the dramatically decreased growth after 50 years for protection AR.

The uncertainty analysis indicates the possibility of higher GHG mitigation of commercial AR than protection AR for both low and high-density plantations (see the lower bounds of ranges in Fig. 1A). These lower bounds reflect optimistic conditions (as defined in SI Note 9) with lower temperature, precipitation, and landfill decay rate, and higher forest carbon yield (Mg C/ha), mill waste recovery rate, soil clay content, and steel usage for traditional buildings (leading to higher material substitution benefits) (see Table S1–S2 for uncertainty analysis inputs). Under the pessimistic conditions, protection AR mitigates slightly more GHGs than commercial AR in the high-density plantations but not low-density plantations (see the upper bounds of ranges in Fig. 1A). Commercial AR has greater ranges of GHG mitigation potential than protection AR given the additional uncertainty of wood product life cycles (contribute to 12–15% of variations, see Table S3). However, protection AR may have larger uncertainties because it is more prone to exposure for longer periods of time to natural disturbances such as insects, diseases, wind, and fire (45), which are not included in this study.

The largest GHG mitigation of S2 and S3 is mainly attributed to CLT substitution and biochar, e.g., CLT substitution accounts for 11% of the total GHG mitigation potential in S2 and S3 (Fig. 1A). Biogenic carbon emissions through biomass decomposition from soil and the plantation ground are the largest GHG emission contributor (Fig. 1B). Converting tree plantation residues to biochar reduces residues left on the plantation floor and soil (zero, 50%, 100% left in S3, S2, and S1, respectively) and therefore reducing emissions from biomass decomposition. Biochar decays slowly (SI Note 8 and Table S4) and decay emissions are minor (Fig. 1B). Biochar also contributes to carbon stock increase (Fig. 1C). CLT and biochar production brings more manufacture-related GHG emissions (light yellow and grey bars) than lumber production (golden bars in Fig. 1B), however, such emission increases are lower than the emission reduction benefits of biochar (brown bars). This result highlights the benefits of removing and converting plantation residues to biochar for GHG mitigation, although the removal rate needs further ecological considerations for maintaining long-term site productivity (see Discussion Section).

Another key factor is CLT substitution, one of the uncertainty sources. Without CLT substitution credits, the comparative conclusions depend on plantation density and thinning practices (Fig. S2C and D). Three density scenarios are 1) low-density plantation (450 trees/acre) without thinning, 2) low-density plantation (450 trees/acre) with thinning 25% of standing in year 10, and 3) high-density (900 trees/acre) with thinning 50% of standing in year 10. On average, without substitution credits, high-density protection AR across 100 years has similar GHG mitigation potentials with innovative commercial AR in S2 and S3 (Fig. S2D). These comparative trends are similar for low density plantations with thinning, however, innovative commercial AR without thinning in S2 and S3 mitigates more GHG than the baseline protection AR on average, even without substitution credits (Fig. S2C). Considering uncertainty, without CLT substitution, all commercial AR in S2 and S3 still mitigate more GHG than protection AR regardless of densities under optimistic conditions, while this is not the case under pessimistic conditions (Fig. S2C and D).

The climate preferability of commercial AR depends on time, e.g., the GHG mitigation potential of S3 including substitution does not exceed the baseline until year 73 and then crosses the baseline several times (Fig. 2A). This can be explained by the temporal changes of GHG emissions and CO₂ sequestration (SI Fig. S3). Thinning low-density plantations delay the time when commercial AR reaches similar GHG mitigation potential as the low-density baseline (Fig. 2A versus Fig. 2B). Besides, thinning a low-density plantation reduces the total 100-year forest carbon sequestered compared to non-thinning (SI Fig. S2). The total carbon stock change shows similar trends as the net GHG balances (Fig. 2D–F).

Overall, the climate change mitigation potential of different AR depends on time, environmental conditions, and material substitution. In the short term (50 years or shorter) and pessimistic conditions in warmer and humid climates within our study region with lower forest carbon yield, soil clay content, and CLT substitution, protection AR is likely to be climate favorable. In general and optimistic conditions in climates that are moderately cooler and dryer within the region of our study with higher forest carbon yield, soil clay content, and CLT substitution, innovative commercial AR is likely to achieve greater GHG mitigation than protection AR and commercial AR with lumber production in the long term (100 years). Without CLT material substitution benefits, compared to protection AR with the same plantation density, low-density commercial AR without thinning is still climate favorable on average and optimistic conditions, while high-density commercial AR with thinning is preferred only under optimistic conditions.

100-year carbon stocks of different carbon pools. The carbon stock results in Fig. 1C highlight the role of AR in increasing the carbon stock of marginal lands. On average, high-density plantations with thinning result in greater carbon stocks than lower density plantations but have larger uncertainty ranges in S2 and S3, because of more collected biomass materials from removed trees during thinning in high-density plantations. In total, high-density plantations in the southeastern US can contribute to on average 1.01 (range: 0.78–1.26), 0.92 (0.69–1.19), 1.03 (0.77–1.35), and 1.12 (0.82–1.48) Gt of carbon storage over 100 years under baseline, S1, S2, and S3, respectively (Fig. 1C).

Thinning affects carbon stocks through its impact on biomass availability. Thinning high-density plantations generates residues for biochar that accounts for 14.0–25.6% of total carbon stock (Fig. 1C). Without thinning, biochar contributions in low-density scenarios are much lower (10.3–19.4% in Fig. 1C). Thinning low-density plantations does not yield higher carbon stocks (Fig. 2D–E) because of the lower production of wood products and biochar (see Fig. S2E). This finding is consistent with other studies indicating that thinning can lower the total standing volume in low-density plantations (46, 47).

In general, high-density plantations with thinning and 100% residue removal yield the highest carbon stock. Commercial plantations demonstrate stable growth in carbon stock every 25 years, whereas protection plantations experience a slowing increase in carbon stock after year 50 (Fig. 2D–F). Carbon sequestered by trees mainly goes to wood products after the first rotation (year 25) in commercial plantations (Fig. 3, detailed carbon flows are shown in Fig. S4). From years 55 and 85, a portion of wood product carbon moves to landfills when lumber and CLT reach their lifetime (lumber: 30 years; CLT: 60 years). A small portion of carbon in litterfall, root, and plantation residues moves to SOC. The remaining sequestered carbon in plantation residues under S2 and S3 goes

to biochar. Compared to protection AR, commercial AR for traditional lumber production has limited capacity to increase carbon storage further, as demonstrated by similar 100-year carbon stock results of S1 and baselines (Fig. 1C). CLT scenarios have greater carbon stock on average than lumber scenarios because of the high carbon stock in CLT and biochar due to their longer lifetime and residence time, respectively (Fig. S4). The total amount of carbon stored in CLT and landfill is slightly higher than the carbon stored in lumber and its landfill over 100 years due to the shorter lifetime of lumber (Fig. 1C). The modeled SOC content increases less in the CLT cases compared to the lumber cases over 100 years because residue removal in the CLT cases results in less plant carbon input to the soil (Fig. 3). However, biochar contributes to a much higher total carbon content in the soils over 100 years in CLT cases compared to the lumber cases (Fig. 3) because biochar carbon has a much longer retention time than SOC (see SI Note 8). It indicates that higher residue removal rate for biochar production results in an overall greater carbon stock increase in soil.

Overall, innovative commercial AR with CLT and biochar demonstrate considerably more carbon stock increases than protection AR and commercial AR with traditional lumber production over 100 years on average and optimistic conditions (in climates that are moderately cooler and dryer within the region of our study with higher forest carbon yield, soil clay content, and CLT substitution). Protection AR has similar or lower carbon stock increase as innovative commercial AR on pessimistic conditions (in climates that are warmer and more humid within the region of our study with lower forest carbon yield, soil clay content, and CLT substitution) across 100 years, but greater carbon stock increase in general within a shorter timeframe. This conclusion is consistent across all scenarios and timeframes (see SI Fig. S2 and Fig. S5 for more details).

Mapped carbon stock change over 100 years. The aggregated carbon stock change on marginal land for each county across 100 years in the southeastern US shows temporal-spatial variations under different scenarios (see Fig. 4). Positive values indicate carbon stock increases compared with year 0 where carbon stocks are assumed to be zero on marginal land. In year 25, most counties are red and orange, indicating a slight carbon stock increase of 0–2 Mt C per county. Some counties in AL, GA, SC, and VA turn blue by year 50, indicating moderate carbon stock increase by 2–5 Mt C per county. By year 75 and 100, more counties in blue and purple indicate substantial carbon stock increases (5 to 12 Mt C).

The spatial pattern of carbon stock increase (Fig. 4) is driven by variations in site index and marginal land availability. For example, some regions (dark red) have minor carbon stock increases across all years, including MS, TN, northern FL, western VA and NC, because of their low marginal land availability and site index (SI Fig. S6). The impacts of site index and marginal land availability differ by region. Eastern SC (the lower coastal plain) has a higher site index than its western areas (the

piedmont and upper coastal plain) (SI Fig. S6A), but western SC yields more carbon stock increases because of the greater availability of marginal land (SI Fig. S6B). Another example is the piedmont of southwestern VA and eastern TN where marginal lands have similar availability, suggesting similar distributions of their site index and carbon stock increases. At the state level, GA achieves the highest 100-year total carbon stock increase (0.38 Gt C) in high-planting density with thinning scenarios, followed by AL (0.28 Gt C) and NC (0.13 Gt C) (SI Table S5). These three states account for 70.5% of the total carbon stock increase of the entire study region. At the regional level, southern GA, southern AL, and southwestern VA (dark purple) demonstrate substantial 100-year carbon stock increase because of their high marginal land availability and high site index (SI Fig. S6). These regions can be priorities for commercial AR on marginal land.

Discussion

This study highlights the importance of strategically considering the combination of available marginal land, AR management, and sustainable wood products as a valid nature-based solution. Our dynamic LCA results suggest that commercial AR on marginal land offers benefits in supplying timber for wood products, mitigating climate change, and establishing a long-term carbon sink. Based on our analysis, commercial AR on marginal land in the southeastern US can supply up to 485.2 million oven dry metric tons of loblolly pine logs for a 25-year rotation. This amount is around nine times of the total annual harvested loblolly pine timber provided by the region (SI Table S6). This additional timber can meet future demands of wood products without converting natural forests to plantations or more intensive management and without losing productive agricultural farmland.

The extent of GHG mitigation benefits depends on wood product, planting density, thinning practices, time, and climate and environmental conditions. Protection AR was estimated to have 10.1 Gt CO₂e yr⁻¹ GHG mitigation potential from 678 Mha of land globally in 2030 (equivalent to 14.9 Mt CO₂e yr⁻¹ per Mha) (26). Our findings show a similar potential with an average of 0.03 Gt CO₂e yr⁻¹ (with 2.1 Mha potential marginal land, equivalent to 14.3 Mt CO₂e yr⁻¹ per Mha) for protection AR. Commercial AR for traditional lumber production shows lower or similar average values of GHG mitigation potential and carbon stock increase with larger uncertainty ranges compared to protection AR, although this study does not model natural disturbances and possible carbon losses resulting from greater exposure to natural disturbances with prolonged forest stocking in protection AR. Commercial AR with CLT and biochar using high-density plantations with thinning and low-density without thinning are more likely to achieve higher long-term GHG mitigation potential than protection AR, especially in moderately cooler and dryer regions in this study with higher forest carbon yield (higher site index region), soil clay content, CLT substitution benefit, and less GHG emissions from soil, forest floor and landfill. But this is not the case in the

shorter term (e.g., 50 years) or warmer and more humid regions with lower forest carbon yield and soil clay content in this study. Given the urgency of GHG mitigation, a mix of protection and innovative AR could be useful to meet near-term climate change mitigation goals while providing a propeller for driving longer-term GHG reduction and carbon storage through innovative wood products and biochar. Considering variations of net GHG balances, commercial AR is more climate favorable than protection AR in moderately cooler and less moist regions with higher site index and soil clay content. Additionally, this study pinpoints the regions where innovative AR can deliver higher carbon stock increase than traditional commercial AR and protection AR in general conditions, including most of Alabama and the Piedmont soils of North Carolina, South Carolina, Georgia, and central southern Virginia, and the Red Hills and Sandhill regions of Georgia and South Carolina. Other economic and social factors related to protection and commercial AR should also be considered for region-specific decision-making.

Our results demonstrate the critical contribution that material substitution can make to maximizing the GHG mitigation potential of innovative wood products. Securing the replacement of carbon-intensive materials such as steel and concrete is essential to reduce GHG and increase carbon stock in buildings (14–17). Although we do not directly model rebound effects and market factors (e.g., price competitiveness between CLT and steel), we evaluated the impacts of variations in material substitution rates. We also do not consider the future decarbonization of steel and concrete. However, even without material substitution, our results show a high possibility of greater GHG mitigation by innovative commercial AR in low-density plantations without thinning than protection AR, though likely not for high plantation density. Future research should consider these factors, such as recent studies (48–50), although none of the previous studies have explored AR on marginal land.

Interestingly, higher plantation residue removal (100% removal) for biochar production contributes to negligible greater GHG mitigation potentials (1.5–1.9% more), although higher carbon stock (4.4–8.7% more) over 100 years than 50% residue removal. 100% removal is an extreme conceptual scenario to explore the maximum possibility, the actual forest removal ratio should be lower given ecological considerations of maintaining soil carbon stocks and associated productivity (51–53). Previous literature recommends retaining at least 33–50% of plantation residues in the US (51) and considering ecosystem services (e.g., biodiversity), when developing region-specific plantation residue removal practices (54–56).

One limitation of this study is the exclusion of the potential social and economic aspects discussed in prior marginal land literature (5, 8). The marginal land used in this study is defined based only on biophysical properties and specific land cover types (4). Whether such marginal lands will be

reforested to plantations depends on additional socioeconomic and cultural values that landowners have, which can be complimentary or in conflict (e.g., hunting, endangered species conservation, recreation, aesthetics, food security) (57–59). In addition, economic circumstances must be considered, such as strong demand for local timber carbon markets and policy incentives. Future AR research should explore the social and economic implications and potential trade-offs between meeting climate objectives and delivering ecosystem services. However, in all circumstances, reforestation for commercial uses needs to plan for set-aside areas for protection that diversify at landscape scales to improve ecosystem services (59–61). This study only considers one tree species, given the challenges of forest modeling and spatial allocation of multiple species on marginal land. Multi-species plantations could provide more stable carbon capture in some tropical and temperate regions, and offer additional co-benefits for ecosystem services (25, 31, 62), which should be considered in future LCA when the challenges above can be tackled.

Active forest management in commercial plantations can potentially reduce fire risk by thinning, periodic harvesting, and residue removal (63) and consequently safeguards carbon stocks, especially at an increased risk of natural disturbances occurrence owing to global climate change. Although natural disturbance is not considered in our analysis, this does not change the conclusion as the disturbance will further decrease the GHG mitigation potential and carbon stock of the protection AR in the long term. In addition, this study does not consider the impact of climate change on forest growth in the future and unusual weather conditions that might happen in some regions. Previous studies for the southern US found growth declines of loblolly pine due to increased temperature (64), but higher productivity for loblolly pine harvested at age 25 due to enriched atmosphere CO₂ concentration (65). Other studies have generally indicated a strong CO₂ fertilization on biomass growth of young forest plantations (66, 67) but not mature forest stands (68). As a result, innovative commercial AR with younger trees will be even more climate beneficial than protection AR considering the influences of natural disturbances and climate change, particularly higher CO₂ concentration. Future research is encouraged to quantify the impacts of climate change on the GHG mitigation efficacy of AR.

Materials and Methods

Life cycle assessment framework. In this study, a cradle-to-grave multi-scale dynamic LCA framework was developed (Fig. S1), which integrated the GIS model, the forest growth model, SOC model, and process-based models of producing wood products (i.e., lumber, CLT, and biochar). A 100-year cut-off time horizon was adopted to be consistent with climate change literature (69). The multi-scale LCA provides insights on product- and regional-scale life-cycle environmental

implications (32). Details in calculating the net GHG emissions and carbon stock change are documented in SI Note 1.

Identification of marginal land in the US. Marginal lands in this study include agricultural lands with challenging soils, pasture lands with challenging soils, and non-stocked forest patches, which are three (in total of 2.1 million hectares) out of ten opportunity classes identified by the study (4). Other land classes, such as shrub and protected areas, are excluded as they either naturally exist and/or provide essential ecosystem services. Post-burned landscapes and frequently flooded areas are excluded as they are vulnerable to natural disturbance. Commercial AR on urban open spaces may bring disturbances to the urban environment, so urban areas are excluded. The GIS data in 30m resolution were collected from (70). The selected three marginal land layers for the southeastern US were downscaled from 30m to 1km pixels by the aggregate by sum technique. All spatial data (Table S7) were processed and visualized by ArcMap 10.8.1 (71).

Forest growth and yield. A growth and yield model (44) was used to simulate forest growth for site-prepared loblolly pine (*Pinus taeda* L.) plantations in the three prominent physiographic regions in the southern US: piedmont, upper coastal plain, and lower coastal plain. The reliability of the model has been demonstrated (72). A demo simulator was used in this study (73). The inputs include site index, physiographic region, planting density, and other silvicultural treatments (73). The annual total dry mass of a whole tree includes litterfall (needles and wood debris biomass that fall on the soil), foliage (living needles biomass), branches (living branch biomass), stem (above-stump stem outside-bark biomass), and roots (coarse root biomass). The calculations for a specific site index are in SI Note 2. All biomass dry mass was transformed to carbon mass using an average carbon content of 50% for wood biomass and foliage (74).

Forest operations. At the beginning of the 25-year rotation, site preparation, herbicide application, and planting are performed (75). During the rotation, fertilizers are applied twice in year 10 and 16. At the end of the rotation, the clear-cut logging harvests standing trees and yields logs (inside-bark), snags, and residues, including foliage and branch. In Scenarios 1–3, logs are transported to produce wood products. In Scenarios 2 and 3, collected residues and snags are chipped on forest sites and then transported for biochar production. The application rate and life cycle GHG emissions of chemicals and fuels used in forest operations are shown in SI Table S8 and S9, respectively. The life cycle GHG emissions of chemicals and fuels were estimated using the ecoinvent 3.6 cut-off database (76), GREET 2021 (77), and literature (77, 78) as documented in SI Table S9-10.

Forest SOC modeling. The SOC changes were simulated by the RothC model (version 26.3) (70), which has been validated and widely used for forestland (79–89). The model was run on a monthly

basis from years to centuries with inputs including monthly carbon inputs, monthly mean temperature, monthly open pan evaporation, monthly precipitation, soil clay content, total SOC content, soil depth, and whether soil is monthly covered (70). The uncollected harvesting residues (including foliage and branches), snags, trees from thinning, roots, and annually generated litterfall are the carbon input to the SOC. The data of soil clay content and total SOC content are from ISRIC-World Soil Information (90). The monthly climate data is an average calculation from 1991 to 2020 derived from the CRU TS 4.05 dataset (91). The output of RothC includes annual total SOC content (Mg C/ha) and annual CO₂ emissions (Mg CO₂/ha). We adopted a method (92) to investigate the impacts of input data uncertainties on RothC results by inputting minimum and maximum values (based on a 95% confidence interval) of predefined input parameters (initial SOC, carbon inputs, temperature, precipitation, and soil clay content) that have the greatest impacts on RothC outputs. More details are available in SI Note 9.

LCA of traditional lumber, CLT, and biochar. Harvested logs are transported to saw mills that includes processes such as debarking, sawing, kiln drying, planing, and power generation (see SI Note 4) (93, 94). Then, lumber are distributed to markets and finally landfilled after their useful lifespan (95). SI Table S11 documents the parameters of saw mill models. The upstream GHG emissions were derived fromecoinvent (76) and GREET 2020 (77). The landfill GHG emissions were estimated using (96, 97) with a consideration of energy recovery (see SI Note 5). CLT has a similar life cycle with lumber but differs in production and end of life. The life cycle inventory (LCI) data of CLT production are documented in SI Note 6 and Table S12. 50% of CLT panel is assumed to be recycled (93), while the rest is landfilled. CLT substitution was estimated based on the traditional structural materials used in the same floor area (17) (see SI Note 6). Logging residues and snags are chipped and sent to a pyrolysis plant for biochar production that was simulated in Aspen Plus (see SI Fig. S7 for the system diagram and SI Note 7 for details). The end-of-life GHG emissions of biochar applied as soil amendment are documented in SI Note 8. The life cycle carbon balances are shown in Fig. S4. This study deploys a two-step uncertainty analysis for wood product systems (see SI Note 9 for details).

Data sharing statement. The information required to reanalyze the data reported in this paper is available within the article and corresponding supporting information.

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Figure Legends

Fig. 1. Net GHG balances, GHG balance breakdown by life cycle stages, and total carbon stock change breakdown by carbon pools of AR on marginal land in the southeastern US at the end of year 100. Net GHG balances under low-density scenarios (S1-3 with or without thinning, L: low density) and high-density scenarios (S1-3 with or without thinning, H: high density) (A). GHG balance breakdown by life cycle stages under low-density scenarios and high-density scenarios (B). Total carbon stock breakdown by carbon pools under low-density scenarios and high-density scenarios (C). Note: the GHG emissions of CLT EOL, Biochar decay, and Forest operation in figures (B) are not visible due to their minimal value compared to others. The maximum ranges of modeled results from uncertainty analysis are shown by the error bars in red. Bars are plotted based on the average values. Numbers in bar charts stand for the average values of the total net GHG balances and total carbon stock change in figure A and C, respectively. The dark green bars for baselines in figure B represent net GHG balances. Detailed calculations and explanations are documented in SI Note 1.

Fig. 2. Net GHG balances and total carbon stock change by different scenarios of AR on marginal land in the southeastern US over 100 years under different scenarios. Net GHG balances (A) Low-density without thinning, (B) Low-density with thinning, (C) High-density with thinning. Total carbon stock change (D) Low-density without thinning, (E) Low-density with thinning, (F) High-density with thinning. These figures are based on average values.

Fig. 3. Total carbon stock change breakdown by carbon pools AR on marginal land in the southeastern US over 100 years under different scenarios. (A) Low density without thinning - Lumber without plantation residue removal, (B) High density with thinning - Lumber without plantation residue removal, (C) Low density without thinning - CLT with 50% plantation residue removal for biochar, (D) High density with thinning - CLT with 50% plantation residue removal for biochar, (E) Low density without thinning - CLT with 100% plantation residue removal for biochar, and (F) High density with thinning - CLT with 100% plantation residue removal for biochar. These figures are based on average values.

Fig. 4. Mapped aggregated carbon stock change from AR on marginal land at county level under high-density with thinning scenarios in the southeastern US in year 25, 50, 75, and 100. (A) Baseline, (B) S1 - Lumber without forest residue removal, (C) S2 - CLT with 50% forest residue removal for biochar, (D) S3 - CLT with 100% forest residue removal for biochar. VA: Virginia, TN: Tennessee, SC: South Carolina, NC: North Carolina, MS: Mississippi, GA: Georgia, AL: Alabama, FL: Florida. Note: the color changes in some areas along state boundaries between TN and AL,

662 MS and AL, and GA and FL are abrupt due to the low availability of site index data of loblolly pine
663 in TN, MS, and FL (see SI Fig. S6A). These figures are based on average values.