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Hurricane damage and forest carbon stocks: evidence from Louisiana

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Abstract

Long-term carbon storage by forests is important for climate mitigation, yet storage durability faces threats from natural disturbances whose causal impacts are not well quantified. We use the staggered timing of two Category 4 hurricanes that struck different regions of Louisiana—Laura in 2020 and Ida in 2021—to estimate the causal effect of severe hurricane damage on forest carbon stocks. Using parish-level data from the USDA forest inventory and analysis program covering all 64 Louisiana parishes over 2017–2024 and a doubly robust difference-in-differences estimator, we find that hurricane damage reduced live biomass carbon by 7%–8%: aboveground live carbon declined 7.3% and belowground live carbon 7.7%, results robust to both cluster-robust and wild cluster bootstrap inference. Total forest carbon—nearly half of which is held in a slow-changing soil pool—declined by 3.5% (95% CI: −6.9% to −0.2%); this aggregate effect is significant under cluster-robust inference but not under the wild cluster bootstrap appropriate for our small number of treated clusters. Effects persisted across the four-year post-treatment period with no evidence of recovery. Live carbon losses were concentrated on private forests (−7.9%, $P = 0.022$), with no detectable change on public forests (+0.9%, $P = 0.892$), though this private–public difference is not statistically significant (interaction $P = 0.493$). We measure changes in carbon stocks rather than net flux to the atmosphere. Because private lands make up 86% of Louisiana's forestland and underpin most carbon offset programs, the magnitude and persistence of these losses suggest that nature-based climate solutions in hurricane-prone regions face greater hurricane-related risks than current carbon-offset frameworks recognize.

1. Introduction

Established forests sequester roughly 2.4Pg C yr^{-1} globally and store an estimated 861Pg C across biomass, soils, dead wood, and litter (Pan *et al* 2011). In the United States, forests and associated wood products offset more than 11% of economy-wide greenhouse gas emissions each year (Domke *et al* 2021), making forest carbon an important component of nature-based climate solutions (Griscom *et al* 2017, Fargione *et al* 2018). These strategies rest on an assumption of durability—that sequestered carbon will remain stored over decadal-to-centennial timescales. This assumption faces two broad threats. Forest loss from land-use change remains a major source of positive carbon emissions from forests globally (Friedlingstein *et al* 2022). In addition, natural disturbances that may be amplified by climate change can convert forests from carbon sinks to carbon sources (Seidl *et al* 2017, Anderegg *et al* 2020), and tropical cyclones pose a particular threat to southeastern U.S. forests that has not been well quantified using causal inference.

Hurricane-driven carbon loss can be large. Chambers *et al* (2007) estimated that Hurricane Katrina killed or damaged approximately 320 million large trees, converting roughly 105Tg C from live to dead biomass—an amount equal to 50% –140% of the net annual U.S. forest tree carbon sink. This single-event figure is comparable to typical annual wildfire carbon emissions across the contiguous United States, yet hurricanes have received less attention in forest carbon policy. Zeng *et al* (2009) estimated that tropical cyclones have affected an average of 97 million trees annually across the United States, causing about 25Tg C yr^{-1} in releases, with impacts concentrated along the Gulf Coast. McNulty (2002) showed that a single intense hurricane can convert 10% of total annual U.S. forest carbon sequestration into dead and downed biomass, with recovery requiring at least 15 years. Climate change may compound this threat: the proportion of major (Saffir–Simpson Category 3–5) tropical cyclones has likely increased over the past four decades (Kossin *et al* 2020, IPCC 2021), rapid intensification events have become more frequent in the Atlantic basin (Bhatia *et al* 2019), and these trends are consistent with anthropogenic forcing (Knutson *et al* 2019, 2020).

Despite these stakes, causal estimates of hurricane effects on forest carbon are absent. Existing studies rely on remote sensing, empirical damage-wind speed models, or pre–post comparisons that do not isolate hurricane effects at the resolution of individual storms and localities (McNulty 2002, Chambers *et al* 2007, Zeng *et al* 2009, Fisk *et al* 2013). A separate gap concerns heterogeneity by land ownership. Private landowners control roughly 86% of southeastern U.S. forestland (Oswalt *et al* 2019, Butler *et al* 2021) and their forests make up the largest component of the regional forest carbon sink (Domke *et al* 2021), yet no study has examined whether hurricane carbon impacts differ between private and public forests—a question with direct relevance to carbon offset programs that operate predominantly on private lands. Private and public forests differ in ways that could affect their vulnerability to wind: private holdings in the South are predominantly younger, even-aged pine plantations of uniform structure, whereas public forests tend to be older and structurally more complex (Fox *et al* 2007, Wear and Greis 2013), and the two differ in their post-storm salvage practices (Prestemon and Holmes 2004).

We address these gaps using a natural experiment created by the staggered landfalls of two Category 4 hurricanes in Louisiana, asking whether severe hurricane damage causally reduced parish-level forest carbon stocks, how any effect was distributed across carbon pools, and whether impacts differed between private and public forests. Hurricane Laura struck southwestern Louisiana on 27 August 2020, with 150-mph winds, damaging forests across 20 parishes (Blazier and Guidry 2020, Pasch *et al* 2021). Hurricane Ida made landfall in southeastern Louisiana on 29 August 2021, also with 150-mph winds, damaging forests across 11 parishes in a geographically distinct region (Guo and Chang 2021, Beven *et al* 2022). We classify the most severely damaged parishes—seven from Laura and four from Ida—as treated; the remaining 53 parishes serve as a never-treated control group. The distinct footprints and staggered timing provide treatment variation for a difference-in-differences design (figure 1). Our primary specification uses the Callaway and Sant'Anna (2021) doubly robust estimator, which addresses known biases in two-way fixed effects (TWFEs) regressions when treatment timing is staggered and effects are heterogeneous (Cengiz *et al* 2019, Goodman-Bacon 2021, Borusyak *et al* 2024, Gardner *et al* 2025). We show robustness across four additional estimators and use multiple inference procedures suited to few-cluster settings (Cameron *et al* 2008, MacKinnon and Webb 2018). Throughout, we measure changes in carbon stocks rather than net flux to the atmosphere, since killed biomass is released only as it decomposes or is removed and some is transferred to long-lived wood products.

2. Data and methods

2.1. Data

Parish-level forest carbon stock data were obtained from the USDA Forest Service forest inventory and analysis (FIA) program for all 64 Louisiana parishes over 2017–2024, retrieved through FIA's online estimation tool EVALIDator (Woodall *et al* 2015, USDA Forest Service 2024) and yielding a balanced panel of $N = 512$ parish-year observations. FIA maintains a systematic grid of permanent sample plots across all U.S. forestland, with approximately one plot per 6,000 acres, measured under an annual panel design in which about one-fifth of a state's plots are remeasured each year and a full cycle is completed in roughly five years. EVALIDator returns FIA's published, pre-computed carbon estimates rather than raw measurements: FIA derives per-tree carbon from field-measured tree dimensions using species-specific allometric biomass equations (Jenkins *et al* 2003) within its standardized national carbon-accounting framework (Woodall *et al* 2015), and models forest floor (litter) and soil organic carbon from stand, site, and geographic attributes rather than field-sampling them at the standard plots (Woodall *et al* 2015, Domke *et al* 2021).

Treatment assignment was based on aerial damage assessments and parish-level timber-loss estimates from the Louisiana Department of Agriculture and Forestry and the LSU AgCenter (Blazier and Guidry 2020, Guo and Chang 2021). Although these assessments reported some timber damage across roughly twenty parishes for Laura, the damage was concentrated; we classified as treated the parishes the assessments ranked in the most severely damaged tier—those with the greatest estimated standing-timber loss and the largest impacted forest acreage (estimated losses above roughly $25 million in both assessments, separated by a clear margin from the remaining parishes). This identified

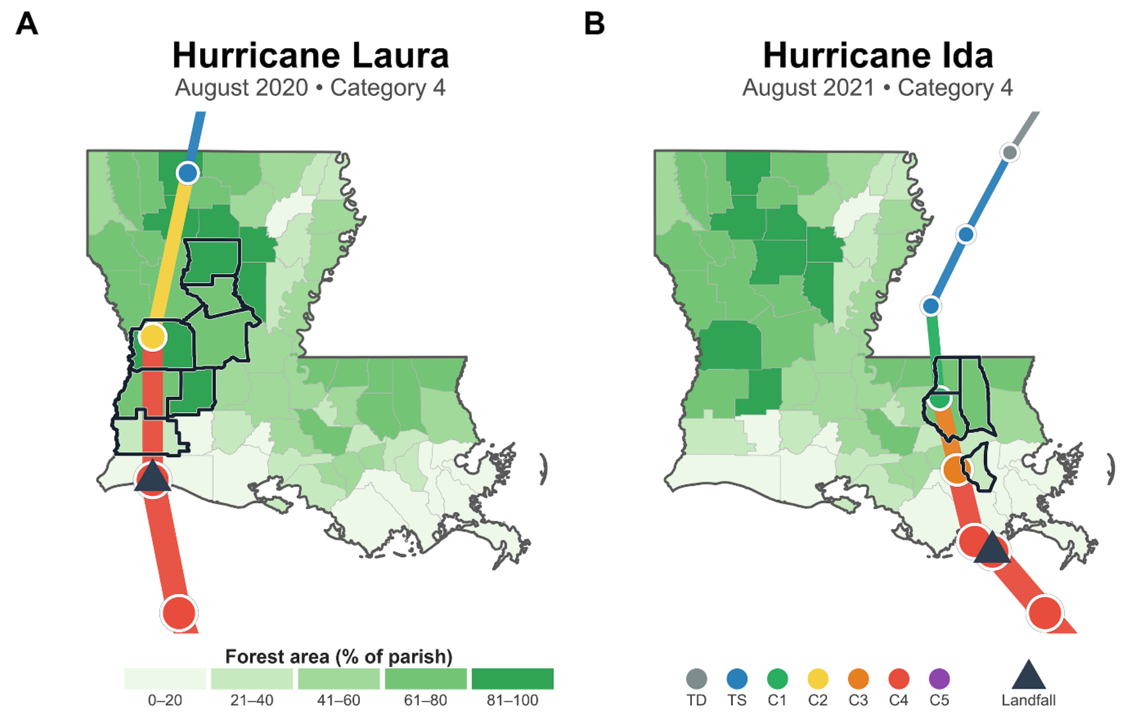

Figure 1. Storm tracks of Hurricane Laura (a) and Hurricane Ida (b) across Louisiana. Color indicates storm intensity at each position along the track: tropical depression (TD, gray), tropical storm (TS, blue), and Saffir–Simpson Categories 1–5 (green through purple). Triangles mark landfall locations. Line width is proportional to maximum sustained wind speed. Parish boundaries shown in gray. Green shading indicates forest area as a percentage of parish area, in five classes from 0%–20% to 81%–100%. Bold outlines mark the parishes classified as treated: the seven Laura-affected parishes in (a) and the four Ida-affected parishes in (b). Storm track data from NOAA/NHC HURDAT2; forest area from FIA.

seven Laura-affected parishes treated beginning in 2020 (Allen, Beauregard, Calcasieu, Grant, Rapides, Vernon, and Winn) and four Ida-affected parishes treated beginning in 2021 (Livingston, St. Charles, St. Helena, and Tangipahoa). The remaining 53 parishes, with lighter or more diffuse damage, serve as a never-treated control group. Laura and Ida were the only Category 4 landfalls in Louisiana during the study period; weaker tropical cyclones caused only minor forest damage and were not separately treated, and the one later landfall, Hurricane Francine (Category 2, 2024), struck an untreated parish, so any effect on controls would bias estimates toward zero (a storm-by-storm account is in the supplementary methods). Treated and control parishes differed at baseline: treated parishes had higher precipitation, lower drought severity, roughly twice the forest area, and higher total carbon, though GDP per capita was similar (supplementary table S1). Three time-varying covariates were included: annual precipitation (PRISM Climate Group 2024); a drought severity index from the U.S. Drought Monitor, computed as the parish-level, area-weighted annual average of that program's weekly drought-category classifications (Svoboda *et al* 2002); and GDP per capita (BEA 2024). Because the design identifies effects from within-parish changes over time, identification rests on parallel pre-treatment trends rather than identical baseline levels; these trends are parallel for every outcome (table 1; supplementary table S7), and precipitation and drought enter the model as time-varying controls.

For the ownership analysis, private forestland includes family forests, corporate timberland, and other private entities; public forestland includes federal (primarily Kisatchie National Forest), state, and local government ownerships. The largest public-forest holdings in our data fall in the inland Kisatchie parishes of Vernon, Rapides, Grant, and Winn, whereas private forest extends across the coastal and southwestern parishes nearest the two landfalls (supplementary table S12). Of 64 parishes, 63 have measurable private forest and 49 have measurable public forest in all years.

2.2. Empirical strategy

Our primary specification uses the Callaway and Sant'Anna (2021) doubly robust difference-in-differences estimator. Define group g as the set of parishes first treated in period g ($g \in 2020, 2021$) and let t index calendar years. The estimator identifies group-time average treatment effects on the treated (ATT)—the average effect of hurricane exposure on carbon stocks for parishes first treated in period g, relative to their no-storm counterfactual:

$$ATT(g,t) = \mathbb{E}[Y_t(g) - Y_t(0) \mid G = g] \quad (1)$$

where $Y_t(g)$ is the potential outcome under treatment timing g and $Y_t(0)$ is the potential outcome under

Table 1. Hurricane effects on total forest carbon: five estimators compared.

Estimator	Effect (%)	*P* value	95% CI	Pre-trend *P*
Two-way fixed effects	−3.5	0.135	[−8.4, 1.2]	0.814
Callaway–Sant'Anna	**−3.5**	**0.039**	**[−6.9, −0.2]**	**0.928**
BJS imputation	−3.3	0.128	[−7.7, 1.0]	0.950
Gardner *et al* two-stage	−3.4	0.106	[−7.7, 0.7]	—
Stacked DiD	−3.7	0.140	[−8.8, 1.3]	—

Note: Outcome is ln(total carbon). All models adjust for parish and year effects, with controls for precipitation, drought severity, and GDP per capita. Standard errors clustered at the parish level. Effect (%) computed as $100 \times \left[\exp\left(\hat{\beta}\right) - 1\right]$. $N = 512$ parish-years. Primary specification in bold.

no treatment. The doubly robust estimand combines inverse probability weighting with outcome regression, providing consistent estimates if either the propensity score or the outcome model is correctly specified (Sant'Anna and Zhao 2020). Group-time effects are aggregated to an overall *ATT* using group-size weights; this overall effect averages the group-time *ATTs* across all available post-treatment years (years 0–4 for the Laura cohort and 0–3 for the Ida cohort) rather than comparing any single pair of calendar years. Standard errors are clustered at the parish level, with simultaneous confidence intervals computed via multiplier bootstrap.

As a benchmark, the traditional TWFE specification is:

$$ln(C_{it}) = \alpha_i + \gamma_t + \beta D_{it} + \mathbf{X}_{it}'\delta + \varepsilon_{it} \quad (2)$$

where C_{it} is the carbon stock in parish i at time t, α_i and γ_t are parish and year fixed effects, D_{it} is a treatment indicator equal to one for hurricane-affected parishes in and after the year of exposure, $\mathbf{X}_{it}$ is a vector of time-varying covariates, and ε_{it} is the error term. The coefficient β is converted to a percentage effect as $\%\Delta = 100 \times \left[\exp\left(\hat{\beta}\right) - 1\right]$. For the coefficient magnitudes observed here (all $\left|\hat{\beta}\right| < 0.09$), this closely approximates $\hat{\beta} \times 100$.

Recent work has shown that TWFE can produce biased estimates when treatment timing is staggered and effects are heterogeneous (Goodman-Bacon 2021, Borusyak *et al* 2024). We therefore supplement the Callaway–Sant'Anna estimator with three additional heterogeneity-robust approaches: the Borusyak–Jaravel–Spiess imputation estimator (Borusyak *et al* 2024), the Gardner *et al* two-stage estimator (Gardner *et al* 2025), and stacked difference-in-differences (Cengiz *et al* 2019).

With only 11 treated parishes, standard cluster-robust inference may overstate precision. We supplement with wild cluster bootstrap (9,999 replications; Rademacher, Mammen, and Webb weights) and randomization inference (10,000 permutations preserving the treatment-time structure) (Cameron *et al* 2008, MacKinnon and Webb 2018). Ownership heterogeneity is tested using a pooled model with a $D_{it} \times \text{Public}_i$ interaction. The minimum detectable effect at 80% power is approximately 5.0% (computed as $2.8 \times \text{SE}$, where $\text{SE} = 0.017$); the observed 3.5% effect implies roughly 54% power. All analyses were replicated in R (version 4.3). Further details on inference procedures, event study specifications, and robustness analyses are in the supplementary material.

3. Results

3.1. Total carbon effects

Hurricane damage reduced total forest carbon in affected parishes by an estimated 3.5% (Callaway–Sant'Anna; $P = 0.039$; 95% CI: −6.9% to −0.2%), a group-size-weighted average over all post-treatment years. The point estimate is stable across all five estimators (−3.3% to −3.7%; table 1, figure 2(a)), but its significance depends on estimator and inference: it is significant under the primary Callaway–Sant'Anna specification with cluster-robust standard errors, but not under the other estimators ($P = 0.11$–0.14) or the wild cluster bootstrap ($P \approx 0.15$–0.17). A Bacon decomposition attributes 97.9% of the two-way fixed-effects weight to clean treated-versus-never-treated comparisons (Goodman-Bacon 2021; Supplementary table S4).

The parallel trends assumption is supported by multiple tests. Pre-treatment coefficients are jointly indistinguishable from zero for both the TWFE specification ($P = 0.814$) and the Callaway–Sant'Anna estimator ($P = 0.928$). Three placebo tests reinforce this conclusion: shifting treatment timing two years earlier produces a nonsignificant estimate ($P = 0.266$), and estimated effects on GDP per capita ($P = 0.442$) and precipitation ($P = 0.655$) are also nonsignificant (supplementary table S5).

The event study (figure 2(b)) shows the trajectory from three years before to four years after hurricane exposure. Pre-treatment coefficients cluster near zero. After the hurricanes, losses appear immediately and generally increase: −2.1% in year 0, −4.2% in year 1, −4.1% in year 2, −4.5% in year 3, and −5.7% in year 4 ($P = 0.049$). The year-four estimate draws only on the Laura cohort, as Ida's window extends to year three (figure 2(c)). No recovery is apparent within the observation window, consistent with evidence that forests require at least 15 years to

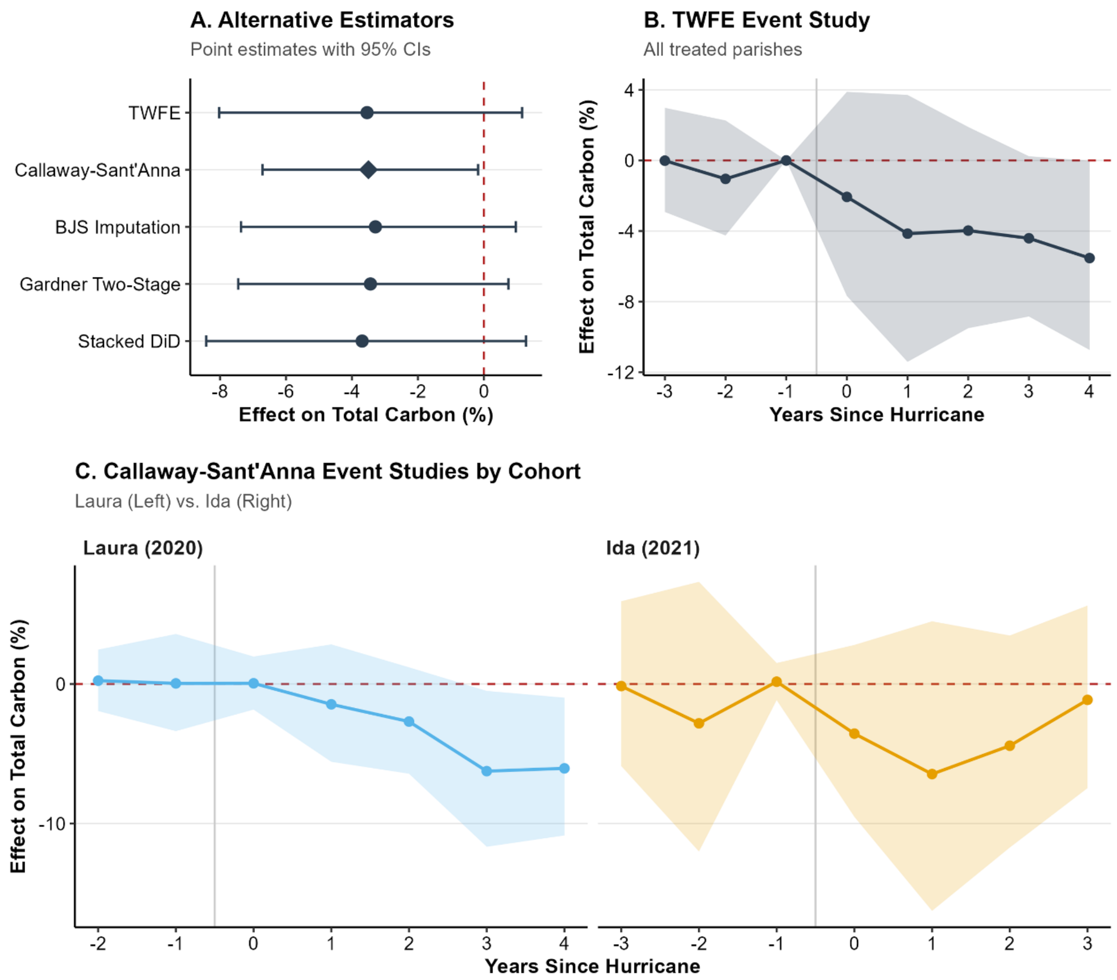

Figure 2. Hurricane effects on total forest carbon. (a) Point estimates and 95% confidence intervals from five difference-in-differences estimators. All estimates fall between −3.3% and −3.7%. The diamond marks the primary Callaway–Sant'Anna estimate; circles denote alternative estimators. (b) TWFE event study from $\tau = -3$ to $\tau = +4$, with $\tau = -1$ as the reference period. Pre-treatment coefficients are near zero (joint $P = 0.814$); post-treatment coefficients reach −5.7% by year four. Shaded area: 95% CIs. (c) Callaway–Sant'Anna event studies for the Laura cohort (left; 7 parishes, treated 2020) and the Ida cohort (right; 4 parishes, treated 2021). Shaded areas: 95% CIs. $N = 512$ parish-years.

recover sequestration capacity after a major hurricane (McNulty 2002) and that hurricane-downed trees take approximately 19 years to convert from a carbon store to a net carbon emission (Tumber-Dávila *et al* 2024). Both hurricane cohorts show negative post-treatment effects (figure 2(c)), though the Ida cohort estimates are less precise given the smaller number of treated parishes (4 vs. 7). Dropping any single treated parish leaves the overall estimate between −2.8% and −4.0%, a maximum deviation of about 0.7 percentage points from the full-sample value (supplementary table S6).

Wild cluster bootstrap P values ranged from 0.153 to 0.165 across three weight distributions, with confidence intervals that include zero. Randomization inference, permuting the cohort labels across parishes, gives a similar $P \approx 0.13$ (supplementary table S2).

3.2. Effects by carbon pool

The 3.5% decline in total carbon obscures a larger impact on pools directly exposed to wind. Total carbon includes soil organic carbon—a large, slow-cycling reservoir that makes up nearly half of all stored carbon. Breaking down by pool shows a gradient of responses (table 2; figure S1).

Aboveground live biomass fell by 7.3% ($P = 0.017$) and belowground live biomass by 7.7% ($P = 0.019$). The slightly larger root effect is expected when whole trees are uprooted (Everham and Brokaw 1996, Peterson 2007). Combined live carbon dropped by 7.4% ($P = 0.017$), and all three estimates remain significant under wild cluster bootstrap. The slower-cycling pools showed no significant change (dead wood −3.8%, $P = 0.360$; litter −1.1%, $P = 0.509$; soil carbon −1.9%, $P = 0.234$). The dead-wood estimate is negative but imprecise, its confidence interval spanning zero (−11% to +4%; Supplementary table S7), so its sign is undetermined; litter and soil carbon are modeled from overstory and stand structure rather than measured directly and turn over on timescales of years to decades, longer than the four years observed here. Total live carbon fell by 7.4%, but live carbon per acre fell by only 5.2% ($P = 0.043$), indicating that

Table 2. Hurricane effects by carbon pool.

Outcome	Effect (%)	P value	Wild bootstrap P
Level outcomes			
Total carbon	−3.5	0.039	0.155
Aboveground live biomass	−7.3	0.017	0.039
Belowground live biomass	−7.7	0.019	0.042
Combined live carbon (AG + BG)	−7.4	0.017	0.041
Aboveground total (live + dead)	−5.7	0.035	0.080
Dead wood	−3.8	0.360	0.557
Litter	−1.1	0.509	0.546
Soil organic carbon	−1.9	0.234	0.433
Density outcome			
Live carbon per acre	−5.2	0.043	0.034

Note: Callaway–Sant'Anna estimates. Effect (%) computed as $100 \times \left[\exp\left(\hat{\beta}\right) - 1\right]$. Wild cluster bootstrap uses Rademacher weights with null imposed (999 replications). AG = aboveground; BG = belowground. $N = 512$. Full results in supplementary table S7.

roughly one-third of the total live carbon loss came from a reduction in forested area rather than lower carbon density within surviving forest.

3.3. Effects by land ownership

Louisiana's forests are predominantly private: in the pre-treatment period, private land accounted for 86.2% of forest area in treated parishes and 86.1% in controls ($P = 0.969$). Yet the two ownership types responded differently to the hurricanes (figure 3; Supplementary table S3).

On private land, hurricanes caused large and statistically significant carbon losses. Live carbon fell by 7.9% ($P = 0.022$), a result that holds under wild cluster bootstrap ($P = 0.046$). Private forest area fell by a marginally significant 2.6% ($P = 0.069$), suggesting conversion of some damaged forestland to other uses. On public land, there was no statistically significant change, though estimates were imprecise given the small number of treated parishes with public forest (9): the point estimate for live carbon was +0.9% ($P = 0.892$), and all other public forest outcomes were close to zero. A formal interaction test places the private–public gap at 8.8 percentage points, but with a large standard error (0.127) it is not statistically significant ($P = 0.493$). The public forest is concentrated in the inland Kisatchie parishes—Vernon, Rapides, Grant, and Winn (supplementary table S12); two treated parishes have no measurable public forest and are excluded. Across every carbon outcome, estimator, and inference method, private forests show negative effects and public forests none (supplementary tables S3 and S11).

3.3.1. Robustness

Estimates are consistent across four covariate specifications, ranging from −3.0% with no controls to −3.5% with all controls (supplementary table S9). All five estimators produce qualitatively consistent results for every carbon pool and ownership category (supplementary tables S10 and S11): total carbon ranges from −3.3% to −3.7% and combined live carbon from −7.4% to −8.8%.

4. Discussion and conclusions

4.1. Mechanisms

The concentration of effects in live biomass pools reflects the primary mode of wind damage to forests: standing trees are the immediate targets, through stem breakage, crown loss, and uprooting (Everham and Brokaw 1996, Peterson 2007). The slightly larger belowground effect likely reflects widespread uprooting, which removes entire root systems from the live carbon inventory. The live carbon lost from standing trees does not all reappear as standing dead wood: it is divided among reduced forested area (roughly one-third of the live-carbon loss), salvage removals that transfer biomass into wood products before it is recorded as dead wood (Prestemon and Holmes 2004), in-place decomposition (Harmon *et al* 1986, Russell *et al* 2015), and the inventory's measurement lag—channels that parish-level stocks cannot separate, so a change in stocks need not translate directly into atmospheric release. The deepening of losses from −2.1% in the first year to −5.7% by the fourth reflects the inventory's measurement lag and the more heavily affected Laura cohort being the only one observed at year four; delayed mortality among storm-weakened trees may also contribute.

Losses fall more heavily on private than public forest. Private holdings in the region are younger, more uniformly structured pine plantations whose canopies present less aerodynamic roughness and meet greater wind force (Mitchell 2013, Gardiner *et al* 2016), and they are more often salvaged after a storm, which removes damaged trees from carbon inventories (Prestemon and Holmes 2004, Stanturf *et al* 2007); public managers more often leave damaged trees in place for ecological purposes (Franklin *et al* 2002, Lindenmayer and Noss 2006). These mechanisms are not mutually exclusive and may reinforce each other. The private–public difference is not statistically significant (interaction $P = 0.493$) and rests on the nine treated parishes that contain public forest.

4.2. Comparison with prior research

McNulty (2002) estimated that a single intense hurricane can convert approximately 10% of annual U.S. forest carbon sequestration into dead and downed biomass. Our 7 –8% reduction measures a different quantity—the share of standing live biomass eliminated in affected parishes, rather than a fraction of annual national sequestration—but both estimates indicate that individual hurricanes can cause

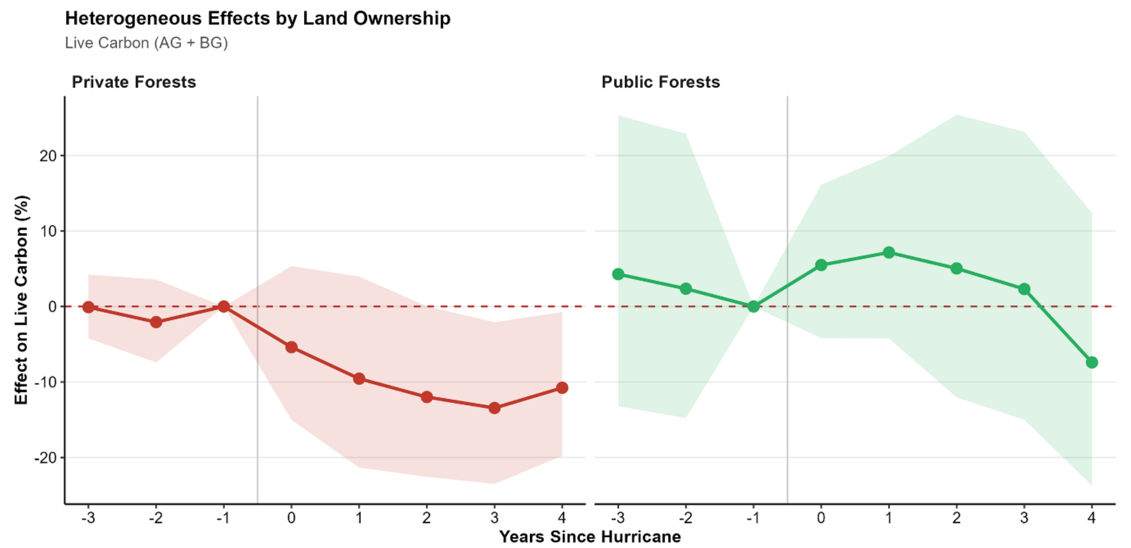

Figure 3. Hurricane effects by land ownership. TWFE event studies for private forests (left; $N = 504$, 11 treated parishes) and public forests (right; $N = 392$, 9 treated parishes). Outcome: combined live carbon (AG + BG). Private forests show flat pre-trends ($P = 0.754$) followed by persistent negative effects (Callaway–Sant'Anna *ATT*: −7.9%, $P = 0.022$). Public forests show flat pre-trends ($P = 0.696$) and near-zero post-treatment effects (+0.9%, $P = 0.892$). Shaded areas: 95% CIs.

large, rapid changes to forest carbon budgets. Recent inventory- and remote-sensing studies document comparable losses across the southeastern United States and the Caribbean but rely on pre–post or wind-field comparisons rather than a contemporaneous control and do not distinguish ownership (Brandeis *et al* 2022, Uriarte *et al* 2019, Hall *et al* 2020, Alam *et al* 2024; see supplementary discussion); the difference-in-differences design used here supplies both. Our total carbon effect of 3.5% is smaller than some prior assessments because total carbon includes soil organic carbon (49% of the total), which changed little; because our difference-in-differences approach identifies the average effect across all treated parishes, including areas with varying damage intensity; and because prior studies often focused on the most heavily damaged stands (Chambers *et al* 2007, Zeng *et al* 2009). The losses persist across the four-year window with no sign of reversal, in keeping with recovery times estimated at 15 years (McNulty 2002) to roughly 19 (Tumber-Dávila *et al* 2024); faster decomposition in Louisiana's warmer climate suggests a shorter timeline here. The continued deepening through year four rests on the Laura cohort alone.

4.3. Implications for forest carbon policy

Carbon offset protocols include buffer pools to address reversal risk. The California Air Resources Board protocol allocates only 3% for catastrophic wind, ice, and flood events combined (Badgley *et al* 2022 a)—an allocation calibrated to a geographically diversified statewide portfolio rather than to the concentrated, repeated exposure our estimates describe in the parishes hit hardest by two consecutive Category 4 storms. Wind damage to forests produces highly skewed damage distributions; at the larger South Central regional scale, annual damages exceeding 5% are rare (Johnston *et al* 2024), so spatial diversification of offset portfolios could partly reduce reversal risk, whereas a portfolio weighted toward hurricane-prone Gulf Coast forests, where damage is spatially correlated, could draw heavily on such a buffer. Because the losses fall disproportionately on the private forest that underpins most offset programs (Sedjo and Sohngen 2012) and show no recovery within our window, credits from private lands in hurricane-prone regions may carry greater reversal risk than current frameworks recognize (Badgley *et al* 2022a, 2022b).

The absence of recovery within four years, together with evidence that full recovery requires at least 15 years (McNulty 2002), raises questions about carbon resilience under repeated hurricane exposure. If hurricanes continue to intensify (Bhatia *et al* 2019, Knutson *et al* 2019, 2020, Kossin *et al* 2020, IPCC 2021) and the interval between major storms shortens, forests in the Gulf Coast region may experience sustained declines in carbon storage capacity. Our study examines carbon stock changes, not net carbon flux to the atmosphere; the net atmospheric impact depends on decomposition rates, post-hurricane management including salvage logging, and recovery trajectories that unfold over longer time horizons.

4.4. Limitations

With only 11 treated parishes, statistical power is limited—approximately 54% for the observed total-carbon effect—and the wild cluster bootstrap *P* values for total carbon (0.15–0.17) lie above conventional thresholds. Many carbon pools and estimators were examined; the combined live-biomass loss is significant under both inference methods and stable across estimators, while individual borderline results such as live carbon per acre ($P = 0.043$) are less certain. The test of differential ownership effects does not reach significance ($P = 0.493$). Under FIA's annual panel design, only about one-fifth of a treated parish's plots are remeasured within a year of a storm, so its damage enters the inventory over roughly five years. The first-year effect is therefore a lower bound, and some of the later deepening reflects this gradual remeasurement rather than continued decline. Our four-year post-treatment window may not capture complete carbon dynamics: cumulative impacts may exceed our estimates, while recovery over the multidecadal horizon suggested by prior research (McNulty 2002) cannot yet be assessed. Parish-level aggregation masks within-parish heterogeneity, and our binary treatment definition does not capture continuous variation in damage intensity. Results pertain to Louisiana and to Category 4 storms; generalization to other regions and intensities requires further study. The central live-biomass result changes little when 2024 is dropped or when treated parishes are removed one at a time (supplementary table S6, supplementary methods).

Future work using plot-level FIA data could test the hypothesized mechanisms underlying ownership heterogeneity—including the roles of stand age, species composition, salvage logging intensity, and post-hurricane land-use conversion—while longer time series would characterize full recovery trajectories.

Acknowledgments

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Data availability statement

The forest, climate, and drought data are publicly available: forest carbon from the FIA Database (https://apps.fs.usda.gov/fia/datamart/), climate from PRISM (https://prism.oregonstate.edu/), and drought from the U.S. Drought Monitor (https://droughtmonitor.unl.edu/). County GDP per capita was obtained through the Lightcast data service under a commercial license and is derived from U.S. Bureau of Economic Analysis county GDP (www.bea.gov/); because the Lightcast series cannot be redistributed, the assembled panel cannot be posted, but the BEA source allows independent reconstruction, and the results are unchanged when this control is omitted (supplementary table S9). Replication code is deposited in the corresponding author's GitHub repository (https://github.com/jinggangguo/ERL).

Supplementary material available at: https://doi.org/10.1088/1748-9326/ae988e/data1.

Conflict of interest

The authors declare no competing interest.

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References

Alam A, Kadam P, Brandeis T, Baeza-castro A and Dwivedi P 2024 Assessing the impact of Hurricane Ivan on aboveground forest carbon dynamics in the Florida Panhandle: a case study from Perdido Bay watershed *For. Ecol. Manage.* **567** 122067

Anderegg W R L *et al* 2020 Climate-driven risks to the climate mitigation potential of forests *Science* **368** eaaz7005

Badgley G, Chay F, Chegwidden O S, Hamman J J, Freeman J and Cullenward D 2022a California's forest carbon offsets buffer pool is severely undercapitalized *Front. For. Glob. Change* **5** 930426

Badgley G, Freeman J, Hamman J J, Haya B, Trugman A T, Anderegg W R L and Cullenward D 2022b Systematic over-crediting in California's forest carbon offsets program *Glob. Change Biol.* **28** 1433–45

Beven J L II, Hagen A and Berg R 2022 Tropical cyclone report: Hurricane Ida (AL092021) (National Hurricane Center)

Bhatia K T, Vecchi G A, Knutson T R, Murakami H, Kossin J, Dixon K W and Whitlock C E 2019 Recent increases in tropical cyclone intensification rates *Nat. Commun.* **10** 635

Blazier M and Guidry K M 2020 Preliminary estimates of the impact of Hurricane Laura to the Louisiana timber industry (LSU AgCenter, in conjunction with the Louisiana department of agriculture and forestry)

Borusyak K, Jaravel X and Spiess J 2024 Revisiting event-study designs: robust and efficient estimation *Rev. Econ. Stud.* **91** 3253–85

Brandeis T, Turner J, Baeza Castro A, Brown M and Lambert S 2022 *Assessing Forest Resource Damage following Natural Disasters Using National Forest Inventory Plots: A Case Study of Hurricane Michael Res. Pap. SRS-65* (USDA Forest Service, Southern Research Station)

Butler B J, Butler S M, Caputo J, Dias J, Robillard A and Sass E M 2021 Family forest ownerships of the United States, 2018 Gen. Tech. Rep. NRS-199 (USDA forest service) *Risk Anal.* National Woodland Owner Survey pp 1056–72

Callaway B and Sant'Anna P H C 2021 Difference-in-differences with multiple time periods *J. Econom.* 225200–30
Cameron A C, Gelbach J B and Miller D L 2008 Bootstrap-based improvements for inference with clustered errors *Rev. Econ. Stat.* **90** 414–27
Cengiz D, Dube A, Lindner A and Zipperer B 2019 The effect of minimum wages on low-wage jobs *Q. J. Econ.* **134** 1405–54
Chambers J Q, Fisher J I, Zeng H, Chapman E L, Baker D B and Hurtt G C 2007 Hurricane Katrina's carbon footprint on U.S. Gulf Coast forests *Science* **318** 1107
Domke G M *et al* 2021 Greenhouse gas emissions and removals from forest land, woodlands, and urban trees in the United States, 1990–2019 resource update FS-307 (USDA forest service)
Everham E M III and Brokaw N V L 1996 Forest damage and recovery from catastrophic wind *Bot. Rev.* **62** 113–85
Fargione J E *et al* 2018 Natural climate solutions for the United States *Sci. Adv.* **4** eaat1869
Fisk J P, Hurtt G C, Chambers J Q, Zeng H, Dolan K A and Negrón-Juárez R I 2013 The impacts of tropical cyclones on the net carbon balance of eastern US forests (1851–2000) *Environ. Res. Lett.* **8** 045017
Fox T R, Jokela E J and Allen H L 2007 The development of pine plantation silviculture in the southern United States *J. For.* **105** 337–47
Franklin J F *et al* 2002 Disturbances and structural development of natural forest ecosystems with silvicultural implications, using Douglas-fir forests as an example *For. Ecol. Manage.* **155** 399–423
Friedlingstein P *et al* 2022 Global carbon budget 2022 *Earth Syst. Sci. Data* **14** 4811–900
Gardiner B, Berry P and Moulia B 2016 Review: wind impacts on plant growth, mechanics and damage *Plant Sci.* **245** 94–118
Gardner J, Thakral N, Tô L T and Yap L 2025 Two-stage differences in differences Working paper
Goodman-Bacon A 2021 Difference-in-differences with variation in treatment timing *J. Econom.* **225** 254–77
Griscom B W *et al* 2017 Natural climate solutions *Proc. Natl Acad. Sci. USA* **114** 11645–50
Guo J and Chang S J 2021 Preliminary estimates of the impact of Hurricane Ida to the Louisiana timber industry (LSU AgCenter, in conjunction with LDAF and U.S. Forest Service)
Hall J, Muscarella R, Quebbeman A, Arellano G, Thompson J, Zimmerman J K and Uriarte M 2020 Hurricane-induced rainfall is a stronger predictor of tropical forest damage in Puerto Rico than maximum wind speeds *Sci. Rep.* **10** 4318
Harmon M E *et al* 1986 Ecology of coarse woody debris in temperate ecosystems *Adv. Ecol. Res.* **15** 133–302
IPCC 2021 *Climate Change 2021: The Physical Science Basis* (Cambridge University Press)
Jenkins J C, Chojnacky D C, Heath L S and Birdsey R A 2003 National-scale biomass estimators for United States tree species *For. Sci.* **49** 12–35
Johnston C M T, Henderson J D, Guo J, Prestemon J P and Costanza J 2024 Unraveling the impacts: how extreme weather events disrupt wood product markets *Earth's Future* **12** e2024EF004742
Knutson T R *et al* 2019 Tropical cyclones and climate change assessment: part I. Detection and attribution *Bull. Am. Meteorol. Soc.* **100** 1987–2007
Knutson T R *et al* 2020 Tropical cyclones and climate change assessment: part II: projected response to anthropogenic warming *Bull. Am. Meteorol. Soc.* **101** E303–22
Kossin J P, Knapp K R, Olander T L and Velden C S 2020 Global increase in major tropical cyclone exceedance probability over the past four decades *Proc. Natl Acad. Sci. USA* **117** 11975–80
Lindenmayer D B and Noss R F 2006 Salvage logging, ecosystem processes, and biodiversity conservation *Conserv. Biol.* **20** 949–58
MacKinnon J G and Webb M D 2018 The wild bootstrap for few (treated) clusters *Econom. J.* **21** 114–35
McNulty S G 2002 Hurricane impacts on US forest carbon sequestration *Environ. Pollut.* **116** S17–24
Mitchell S J 2013 Wind as a natural disturbance agent in forests: a synthesis *Forestry* **86** 147–57
Oswalt S N *et al* 2019 Forest resources of the United States, 2017 *Gen. Tech. Rep.* WO-97 (USDA forest service)
Pan Y *et al* 2011 A large and persistent carbon sink in the world's forests *Science* **333** 988–93
Pasch R J, Berg R, Roberts D P and Papin P P 2021 *Tropical Cyclone Report: Hurricane Laura (AL132020)* (National Hurricane Center)
Peterson C J 2007 Consistent influence of tree diameter and species on damage in nine eastern North America tornado blowdowns *For. Ecol. Manage.* **250** 96–108
Prestemon J P and Holmes T P 2004 Market dynamics and optimal timber salvage after a natural catastrophe *For. Sci.* **50** 495–511
PRISM Climate Group 2024 PRISM gridded climate data (Oregon State University) (available at: https://prism.oregonstate.edu/)
Russell M B, Fraver S, Aakala T, Gove J H, Woodall C W, D'amato A W and Ducey M J 2015 Quantifying carbon stores and decomposition in dead wood: a review *For. Ecol. Manage.* **350** 107–28
Sant'Anna P H and Zhao J 2020 Doubly robust difference-in-differences estimators *J. Econom.* **219** 101–22
Sedjo R A and Sohngen B 2012 Carbon sequestration in forests and soils *Annu. Rev. Resour. Econ.* **4** 127–44
Seidl R *et al* 2017 Forest disturbances under climate change *Nat. Clim. Change* **7** 395–402
Stanturf J A, Goodrick S L and Outcalt K W 2007 Disturbance and coastal forests: a strategic approach to forest management in hurricane impact zones *For. Ecol. Manage.* **250** 119–35
Svoboda M *et al* 2002 The drought monitor *Bull. Am. Meteorol. Soc.* **83** 1181–90
Tumber-Dávila S J *et al* 2024 Hurricanes pose a substantial risk to New England forest carbon stocks *Glob. Change Biol.* **30** e17259
U.S. Bureau of Economic Analysis 2024 Regional economic accounts: GDP by County (available at: www.bea.gov/)
Uriarte M, Thompson J and Zimmerman J K 2019 Hurricane María tripled stem breaks and doubled tree mortality relative to other major storms *Nat. Commun.* **10** 1362
USDA Forest Service 2024 Forest inventory and analysis national program (available at: www.fia.fs.usda.gov/)
Wear D N and Greis J G (eds) 2013 *The Southern Forest Futures Project: Technical Report Gen. Tech. Rep.* SRS-178 (USDA Forest Service)
Woodall C W *et al* 2015 The U.S. forest carbon accounting framework: stocks and stock change, 1990–2016 *Gen. Tech. Rep.* NRS-154 (USDA forest service)
Zeng H, Chambers J Q, Negrón-Juárez R I, Hurtt G C, Baker D B and Powell M D 2009 Impacts of tropical cyclones on U.S. forest tree mortality and carbon flux from 1851 to 2000 *Proc. Natl Acad. Sci. USA* **106** 7888–92