The Impact of Carbon Fertilization On Forest Growth

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The U.S. forest carbon sink:

1) sequesters ~700-800 million tons CO_2 per year
2) offsets about 10% of U.S. carbon emissions

US Biennial Review, 2016
US EPA, 2019
Pan et al., 2011

Based on assumption that sink was stable/growing,

US made Paris Accord pledge
To reduce CO_2 emissions 26-28%

US Department of State, 2016

If US maintains robust carbon sink, achieving future carbon-emission reductions will be cheaper

US Mid-Century Report, 2016

Many explanations for why America has such a large forest sink:

1) Forest Management
2) Climate Change
3) Age Composition
4) Carbon Fertilization

But the role of fertilization and management are not well explained in the literature

Climate Change v Carbon Fertilization

Climate change has been tied to reduced yields

Miao et al., 2016

In agriculture, exposure to temps above 30^{0}C has been shown to reduce yields

Ortiz-Bobea et al., 2019

By the end of century, yields for cotton, soybeans and corn will decrease ~30 to 82%

Schlenker and Roberts, 2009

Difficult to disentangle carbon fertilization from technological change, as

both gently increase over time &

crops only exist for one year

Thus, unable to say if yield declines will be offset by carbon fertilization

Climate Change, Carbon Fertilization & Technological Progress

Empirical identification requires us to consider the challenge that:

Climate change impacts vary temporally and spatially

CO_2 concentrations vary only temporally

US Forest Service plot-level data provides age class information

Can be used to identify the effect of exposure to CO_2 concentration

While controlling for other site-specific factors

We exploit two key features for empirical identification

1) Ability to observe trees of same age class & at different time periods with different CO_2 exposure
2) Ability to examine the small set of tree species that grow both with & without much human intervention

Thus, can isolate role of technological progress apart from carbon fertilization

Research Questions

What is impact of increased atmospheric CO_2 on biomass?

What is magnitude of impact relative to climate change?

Is impact consistent across major U.S. forest species?

What has been effect of forest management on biomass?

Data

USFS Forest Inventory and Analysis Program for:

- Volume per hectare data
- Plot conditions

PRISM Climate Group for:

- Precipitation data
- Temperature data

National Atmospheric Deposition Program for:

- Nitrogen deposition volumes

National Oceanic and Atmospheric Administration for:

- Atmospheric carbon dioxide levels

Forest Groups

1. Oak/Hickory
2. Elm/Ash/Cottonwood
3. Oak/Gum/Cypress
4. Maple/Beech/Birch
5. White/Red/Jack Pine
6. Loblolly/Shortleaf Pine
7. Spruce/Fir
8. Slash/Longleaf Pine
9. Aspen/Birch

Model 1: Matching Model

Base Model Controls

1. Stand Age (1 to 100 years)
2. Site Class (Class 1 to 6)
3. Elevation (Feet)
4. Slope (Angle, as percent)
5. Aspect (Null/North/South)
6. Physiographic Class (Xeric/Mesic/Hydric)
7. Lifetime Mean Temperature (°C)
8. Lifetime Mean Precipitation (mm/month)
9. Land Ownership (Public/Private)
10. Regrowth Method (Reseeded/Natural)
11. Disturbance (Presence/Absence)
12. Treatment (Presence/Absence)

Approach

- One-to-one matching
- With & without replacement
- With ties = TRUE
  - ✓ Multiple matches results in weighted average
- Caliper: ≤0.2 standard deviations
- Estimated treatment effect on treated
  - ✓ ATT
- Used 1 node & 28 cores of supercomputer
- Calculated mean standardized differences
  - ✓ In eQQ plots for each variable
- Optimized QQmean.max
  - ✓ Minimized max of these differences
- Wait generations = 10
  - ✓ Process halted if no change over 10 generations

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Model 2: Panel Model

$$LnVolumePerHectare = \beta_0 + \beta_1*(LnLifetimeCO_2) + \beta_2*(LnLifetimeCO_2 * RegrowthMethod) + \beta_3*(1/StandAge) + \beta_4*(RegrowthMethod) + \beta_5*(SiteClass) + \beta_6*(SeasonalLifetimeMeanTemperature) + \beta_7*(SeasonalLifetimeMeanPrecipitation) + \beta_8*(PhysiographicClass) + \beta_9*(Ownership) + \beta_{10}*(Slope) + \beta_{11}*(Elevation) + \beta_{12}*(Aspect) + \beta_{13}*(Treatments) + \beta_{14}*(Disturbances) + \beta_{15}*(Latitude) + \beta_{16}*(Longitude) + \varepsilon$$

LnVolumePerHectare: Natural log of net volume of wood/acre in central stem of trees: (m^3/ha)

$LnLifetimeCO_2$: Natural log of cumulative lifetime exposure to CO_2

β_3 to **β_{16}**: Control variables

FE: County fixed effects

ε: Error term

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Result 1

Carbon fertilization has increased biomass in U.S. forests by as much as 30-50% depending on the species.

	White/Red/Jack	Spruce/Fir	Slash/Longleaf
Δ (%)	42.6	44.4	28.8
	Loblolly/Shortleaf	**Oak/Hickory**	**Oak/Gum/Cypress**
Δ (%)	19.3	15.4	8.3
	Elm/Ash/Cottonwood	**Maple/Beech/Birch**	**Aspen/Birch**
Δ (%)	1.2	30.1	9.2

Table 1. Percentage-Point Change in Biomass, On Unmanaged Plots, At 50 Years of Age, By Forest Type, Using Matching Model, For Stands Aged 1 to 100.

Note: Propensity score model was run with a pre-period using observations from 1968 to 1990 and the post-period using observations from 2000 to 2018.

These results
are similar
(robust)
in the two models
(matching and panel).

	White/Red/Jack	Spruce/Fir	Slash/Longleaf
Δ (%)	21.4	20.9	18.0
	Loblolly/Shortleaf	**Oak/Hickory**	**Oak/Gum/Cypress**
Δ (%)	18.4	17.1	18.2
	Elm/Ash/Cottonwood	**Maple/Beech/Birch**	**Aspen/Birch**
Δ (%)	18.8	18.7	20.1

Table 2. Percentage-Point Change in Biomass, On Unmanaged Plots, At 50 Years of Age, By Forest Type, Using Panel Model, For Stands Aged 1 to 100.

Note: Propensity score model was run with a pre-period using observations from 1968 to 1990 and the post-period using observations from 2000 to 2018.

Result 2a

The effects of carbon fertilization are robust to management.

Result 2b

Management greatly increased biomass, with the largest increase in Loblolly, and the smallest increase in White/Red/Jack Pine.

(years)	% Δ from Carbon Fertilization 20	30	% Δ from Forest Management 20	30	% Δ from Both Inputs 20	30	# of Obs
Loblolly/Shortleaf	32.2	28.9	22.3	57.6	54.5	86.5	175,476
Slash/Longleaf	32.2	28.9	16.3	56.5	48.5	85.4	41,145
White/Red/Jack	30.4	27.3	7.2	17.6	37.6	44.9	36,268

Table 3. Percentage-Point Change in Biomass, From 1960 to 2017, By Pine Forest Type, By Age, Based on All Observations for Stands Aged 1 to 100.
Note: The change due to Forest Management is the average of the within-year differences for 1960 and 2017. The changes for Carbon Fertilization and Climate are a calculated difference between the expected volume in 1960 and 2017, with those figures calculated as the age-specific lifetime exposure in each year.

Result 3

Changes in temperature & precipitation have had both positive & negative effects on biomass in US forests since 1960, but the overall effect has largely been positive.

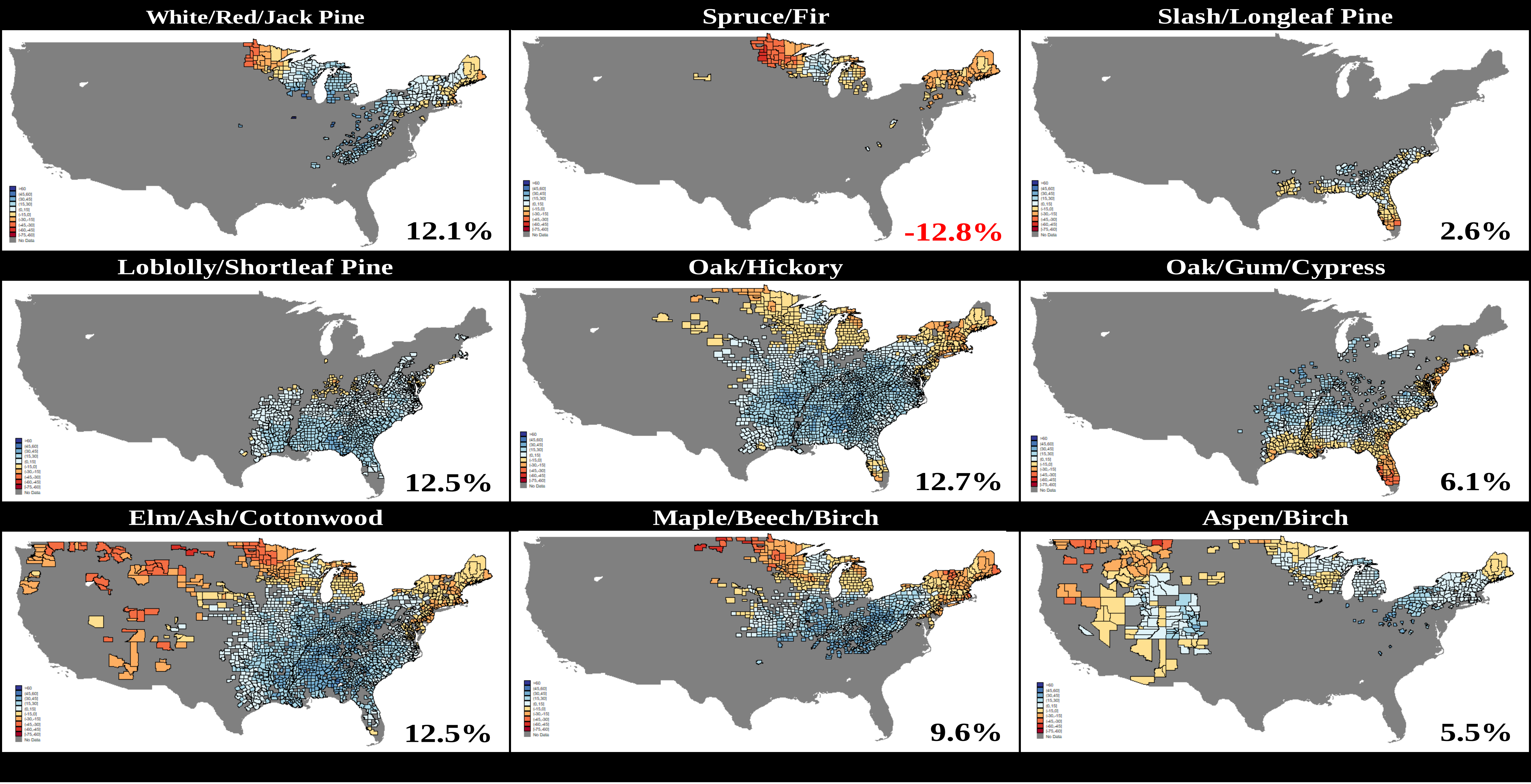

Figure 1. Biomass Change, Due to Changes in Temperature & Precipitation, From 1960 to 2017, By Forest Type, In 50-yr Old Stands, By County, Based on Observations for Unmanaged Stands Aged 1 to 100.

Note: The numerical values in the bottom right of each pane represent the average county impact.

Result 4

Across a selection of states with observations from the 1970s to the present:

1. Carbon fertilization has had a positive effect on biomass
2. Climate has had mostly a negative effect
3. Age class shifts have both increased & decreased biomass

	CO_2	Climate	Age Composition	Area	Total
White/Red/Jack	19.9%	-8.1%	10.1%	7.1%	29.1%
Spruce/Fir	19.0%	-16.5%	31.9%	7.7%	50.2%
Slash/Longleaf	17.9%	-11.3%	-5.9%	-27.7%	-26.9%
Loblolly/Shortleaf	19.1%	9.6%	-13.7%	27.3%	48.1%
Oak/Hickory	16.1%	-4.3%	9.4%	9.2%	35.5%
Oak/Gum/Cypress	15.5%	-10.7%	-10.2%	-9.2%	-15.9%
Elm/Ash/Cottonwood	17.1%	-6.7%	-7.2%	33.1%	35.2%
Maple/Beech/Birch	15.1%	-11.0%	10.0%	-8.3%	1.3%
Aspen/Birch	19.2%	-8.3%	-2.1%	-13.3%	-9.9%

Table 4. Key Drivers of Biomass Change, From 1974 to 2017, In 11 States, In Percentage-Points, By Forest Type, In Unmanaged Stands, Ages 1 to 100.
States are AL, AR, FL, GA, LA, MN, MS, NC, SC, TX, & VA. Age composition and area were calculated for 11 states using evaluation closest to 1974 (range: 1968 to 1977) and 2017 (range: 2017 to 2017). The change due to Forest Management is the sum of the predicted volume by age decile multiplied by the forested area in that age decile for years 1974 and 2017. The changes for Carbon Fertilization and Climate are a calculated difference between the expected volume in 1974 and 2017, with those figures calculated as the age—decile-specific lifetime exposure in each year.

Questions?

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