**Title:** Nuisance species compromise the carbon sequestration potential in an Eastern US temperate deciduous forest

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*(Word limit: 6,500 words)*

# Summary

\*Summary formats tend to be in a few long bullet points

Temperate deciduous forests play a critical role in the global carbon (C) cycle, accounting for a substantial portion of the global forest C sink. The dominant view imbued in Earth System Models is that, at least within the eastern United States, the biome is likely to remain a C sink throughout the 21st century. However, these models do not incorporate nuisance species – *i.e.*, species whose local abundance has increased as a result of human activities and that are causing ecological harm. Nuisance species are known to increase tree mortality (*e.g.*, non-endemic pests and pathogens) and decrease recruitment (*e.g.*, deer and non-endemic plants) throughout the temperate deciduous biome, yet the net effect on current and future C cycling is unknown. Here, we use 15 years of detailed census data from a large (25.6 ha) forest dynamics plot in a Mid-Atlantic temperate forest, including a 4-ha deer exclosure, to understand how nuisance species are affecting C cycling. We show increased biomass mortality, a net reduction in aboveground C storage, and decreased abundance of canopy tree species in the understory. Under current trends this forest will continue to lose C sequestration capacity, indicating that the C sequestration of temperate deciduous forests is likely overestimated.

**Keywords**:

# 1 Introduction

The temperate forest biome plays a critical role in the global carbon cycle, accounting for almost half of the net global forest carbon (C) sink (Harris *et al.*, 2021), with deciduous forests representing a substantial portion of this, sequestering >300 Tg C yr-1 (Pugh *et al.*, 2019). Although currently a C sink, the future of the biome remains uncertain. The dominant view imbued in Earth System Models is that, at least within the eastern US, the biome is likely to remain a C sink for the remainder of the 21st century (Finzi *et al.*, 2020; Wu *et al.*, 2023), albeit with declining CO2 sequestration capacity (Ahlström *et al.*, 2012). Yet, global C models predict a wide range of future trajectories of CO2 sequestration (Ahlström *et al.*, 2012; Arora *et al.*, 2020), and current global C models do not represent some influential mechanisms (e.g., Fatichi *et al.*, 2014; Clark *et al.*, 2021). One mechanism that is not represented in global C models is the impact of nuisance species – i.e., endemic or non-endemic species that, as a result of human influence, have much greater abundance in an ecosystem than they did historically, resulting in undesirable ecological consequences (**refs?**). Similarly, the impact of nuisance species on forest carbon budgets is not considered in machine learning/niche models that seek to project future forest distribution and carbon stocks (**?** Wu *et al.*, 2023), nor in carbon offset projects (**???** **refs?**). This is problematic in that nuisance species – including non-endemic insect pests and pathogens, non-endemic plants, and over-abundant herbivores – are dramatically impacting carbon cycling in temperate deciduous forests around the world, as described below.

## 1.1 (paragraph on tree mortality from non-endemic pests and pathogens)

Non-endemic pests and pathogens have been important driver of mortality (Anderson-Teixeira *et al.*, 2021). These can reduce C and need to be considered in future climate change projections.

Fei *et al.* (2019)

Non-endemic pests and pathogens facilitate invasin of non-endemic plants (Guo *et al.*, 2023 and refs therein).

## 1.2 (paragraph on recruitment failure because of deer and non-endemic plants)

* white-tailed deer (*Odocoileus virginianus* ) is important endemic nuisance species, over-abundant because of human influence

McGarvey *et al.* (2013) Holm *et al.* (2013) Knauer *et al.* (2023)

The capacity to regenerate following disturbances, including ongoing gap formation through mortality of canopy trees, critically influences long-term forest dynamics. Regeneration depends first upon seed production and then upon seedling recruitment, survival, and growth into trees. When any one of these steps fails, the stage is set for disturbance to push forest ecosystems over a tipping point, whereby there is little chance that a forest will recover to it’s pre-disturbance state in the foreseeable future (**refs?**). Global change pressures can set the stage for such critical transitions by gradually shifting baseline conditions, making post-disturbance recovery unlikely despite the persistence of mature trees (Anderson-Teixeira *et al.*, 2013; McDowell *et al.*, 2020; **refs?**). In the mid-Atlantic region of eastern North America, forests face a severe “regeneration debt”, meaning that there are insufficient juveniles of current canopy tree species to replace the mature cohort when they eventually die (Miller & McGill, 2019; Miller *et al.*, 2023). Low juvenile abundance in the region is driven by a combination of over-abundant deer, competition with non-endemic species, and possibly climate change (Russell *et al.*, 2017; Miller & McGill, 2019; Gorchov *et al.*, 2021; Miller *et al.*, 2023). Deer are the biggest problem (Gorchov *et al.*, 2021). The juveniles that are present tend to represent a different, more mesophytic set of species (*Acer spp.*, *Fagus grandifolia*) than currently dominate much of the region (*Quercus spp.*, *Carya spp.*, Miller & McGill (2019); Nowacki & Abrams (2015)]–a dynamic driven by fire suppression and mesophication (**refs?**).

Here, we use 15 years of detailed census data from a large forest dynamics plot including a 4-ha deer exclosure to test the following hypotheses: (1) C stocks have declined (-∆AGB) (2) canopy tree mortality and associated biomass loss are increasing, in large part due to non-endemic nuisance species (pests & pathogens) (3) recruitment (outside deer exclosure) and growth have not kept pace with tree mortality, implying that future mortality will result in substantial net biomass loss (regeneration debt)

# 2 Materials and Methods

## 2.1 Study site

The study was conducted at The Smithsonian Conservation Biology Institute’s (SCBI) large forest dynamics plot in Front Royal, Virginia, USA (38.8935°, -78.1454°; Bourg et al. 2013, Anderson-Teixeira et al. 2015). *A sentence about the region and that it is adjacent to the northern entrance of Shenandoah National Park.* The plot is 25.6 ha (640 x 400 m) and includes a 4-ha, 2.4 m high deer exclusion fence, which has decreased the number/decreased the presence of white-tailed deer since 1990 (McShea 2000). It consists of a mature secondary eastern deciduous forest that developed following logging and agricultural use in the mid-19th century. The species composition reflects what is typical of this forest type, with a canopy that is dominated by tulip poplar (*Liriodendron tulipifera*), oak (*Quercus spp.*), and hickory (*Carya spp.*), and the understory that is primarily composed of spicebush (*Lindera benzoin*), paw-paw (*Asimina triloba*), American hornbeam (*Carpinus caroliniana*), and witch hazel (*Hamamelis virginiana*)

*Which definition of forest type is more accurate - mature, mixed deciduous forest or mature secondary eastern deciduous forest?*

*Need to add the Anderson-Teixeira et al. 2015 reference to references page*

In addition to our consideration of the plot as a whole, we give special consideration to three portions of the plot, all upland forest (i.e., excluding low-lying areas around streams): (1) low deer, low non-endemic insects & pathogens (Fig. 1a)- 4 ha portion of upland forest in the SE quarter of the plot, fenced in YEAR and maintained with only occasional deer presence for the past ## years and with relatively low abundance of canopy species affected by non-endemic pests and pathogens; (2) high deer, low non-endemic insects & pathogens (Fig. 1b) - # ha of upland forest outside the deer exclosure with relatively low abundance of canopy species affected by non-endemic pests and pathogens; (3) high deer, high non-endemic insects & pathogens (Fig. 1c) - a # ha section of upland forest outside the deer exclosure with relatively high abundance of canopy species affected by non-endemic pests and pathogens. These areas were delineated as follows. Upland forest was defined according to topographic wetness index, originally calculated for the SCBI plot in McGregor *et al.* (2021). Vulnerability to non-endemic insects & pathogens was defined based on the abundance of canopy species affected by non-endemic pests and pathogens at the time of plot establishment (2008).



**Figure 1. Photos within the SCBI ForestGEO plot: (a) low deer, low non-endemic insects & pathogens, (b) high deer, low non-endemic insects & pathogens, (c) high deer, high non-endemic insects & pathogens**  *(add a map of the plot)* All photos taken September 2023 by K. Anderson-Teixeira.

## 2.2 Data collection

*(describe main census & years occurred)*

Data was collected according to the standard ForestGEO protocol, outlined in (Condit 1998). A census crew measured the diameter at breast height (DBH), mapped, and tagged every stem on the plot with a DBH greater than or equal to 1 cm. DBH was recorded only for living trees. If there were multiple stems on a tree, each stem was measured and given a stem number and tag.

*(describe mortality census)*

In addition to the ForestGEO census, an annual [official name of mortality survey] is conducted on the large forest dynamics plot. The survey assesses the health of individual trees and identifies factors that contribute to mortality. The survey was initiated in 2008, and has been conducted every year since 2013. (source). The field crew measured the percentage of the crown that was alive and intact, and noted any factors associated with death (i.e. wounds) present on the tree. Numerous nuisance species and pathogens, including the emerald ash borer, white-tailed deer, and dutch elm disease have been recorded in the region prior to the start of the mortality survey (Herms & McCullough, 2014, McShea 2000,NEED ELM SOURCE).

*(describe invasive plants survey)*

*(describe seedlings survey, if used)*

*(describe QA/QC and technical workflow)*

Field data was collected on Apple iPads using the ESRI ArcGIS Field Maps application. To improve the quality of the data, GitHub Actions continuous integration was implemented for quality control (Kim et al., 2022). Data from the previous census was used to populate the Field Maps app, and fields were created to input data. There were checks built into the app to help catch errors, for example the DBH field would flag a suspiciously high number and would not allow the form to be submitted if it was blank. To use the app in the field the census crew downloaded offline areas of where they were working and synced them to an online map after collecting data. Next the data was downloaded from ArcGIS online and pushed to GitHub, where it triggered a GitHub Action running data quality assurance and control (QA/QC) scripts. The scripts were written in R and checked the data for errors such as “suspicious positive growth.” After going through the QA/QC process, a csv of errors and warnings with the associated stem were output which could then be corrected in the field.

## 2.3 Analyses

apply the metric of Miller *et al.* (2023) to determine imminent failure/ probable failure/ insecure/ secure?

# 3 Results

# 4 Discussion

Holtmann *et al.* (2021)

# 5 Conclusions (optional) *(No Conclusions section listed in Submission Guidelines)*

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# Competing Interests

The authors declare no conflict of interest.

# Author Contributions

*[Name of author 1] and [Name of author 2] conceived the ideas and designed methodology; [Name of author 1] and [Name of author 3] collected the data; [Name of author 2] and [Name of author 4] analysed the data; [Name of author 1] and [Name of author 4] led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.*

# Data availability

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# 6 Supporting Information