Unravelling Forest Complexity: Resource Use Efficiency, Disturbance, and the Elusive Structure-Function Relationship

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Abstract

Structurally complex forests optimize light and water resources to assimilate carbon more effectively, leading to higher productivity. Information obtained from Light Detection and Ranging (LiDAR)-derived structural complexity (SC) metrics across spatial scales serves as a powerful indicator of ecosystem-scale functions such as gross primary productivity (GPP). However, our understanding of mechanistic links between forest structure and function, and the impact of disturbance on the relationship, is limited. Here, we paired eddy covariance measurements of carbon and water fluxes in temperate forests collected in the CHEESEHEAD19 field campaign with drone LiDAR measurements of SC to establish which SC metrics were strong drivers of GPP, and tested potential mediators of the relationship. Mechanistic relationships were inspected at four metric calculation resolutions to determine whether relationships persisted with scale. Vertical heterogeneity metrics were the most influential in predicting productivity for forests with a significant degree of heterogeneity in management, forest type, and species composition. SC metrics included in the structure-function relationship as well as the strength of drivers was dependent on metric calculation resolution. The relationship was mediated by light use efficiency (LUE) and water use efficiency (WUE), with WUE being a stronger mediator and driver of GPP. These findings allow us to improve representation in ecosystem models of how SC impacts light and water-sensitive processes, and ultimately GPP. Improved models enhance our ability to simulate true ecosystem responses to management, resulting in a more accurate assessment of forest responses to management regimes and furthering our ability to assess climate mitigation and strategies.

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UNRAVELING FOREST COMPLEXITY

Resource Use Efficiency, Disturbance, and the Structure-Function Relationship

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Motivation

Mapping mechanistic links between forest structure and function is fundamental to scaling measurements from the leaf → stand → landscape level

- Structural complexity (SC) characterizes the 3D arrangement of vegetation, & constrains the forest's ability to assimilate available resources for photosynthesis
- Synthesis of information from SC metrics across spatial scales can serve as a powerful indicator of ecosystem-scale functions such as gross primary productivity (GPP)
- Identifying which SC variables are the strongest drivers of GPP & what potential controls of the structure-function relationship exist is a vital aspect of this effort

Research Questions

1. Which SC metrics are the strongest drivers of GPP in mixed temperate forests with a high degree of heterogeneity and management?
2. How do management legacies impact SC metrics and stand productivity?
3. Is the mechanistic relationship between forest structure and function direct, or is it mediated by resource use efficiency (RUE)?
4. Is the mechanistic relationship between forest structure and function dependent upon the scale of structural metric calculation?

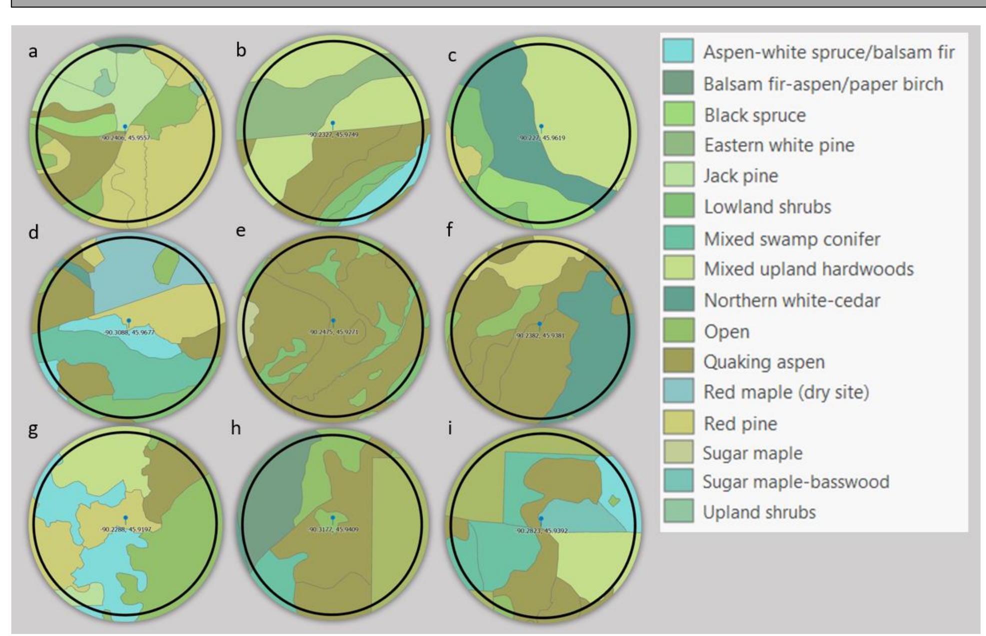


Figure 1. Vegetation coverage at each of the nine forested sites: **a)** NE2 **b)** NE3 **c)** NE4 **d)** NW2 **e)** SE3 **f)** SE5 **g)** SE6 **h)** SW2 and **i)** SW4. Coverage is segmented by both vegetation type and stand age.

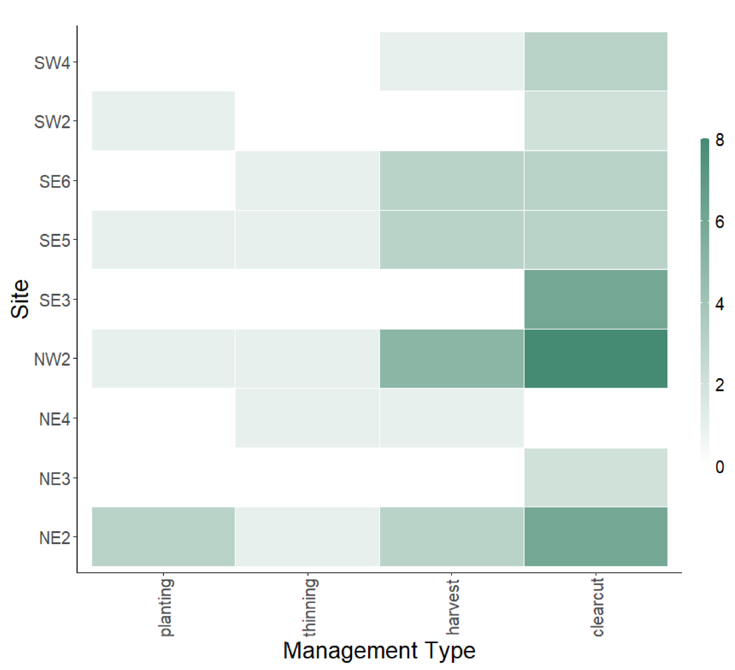
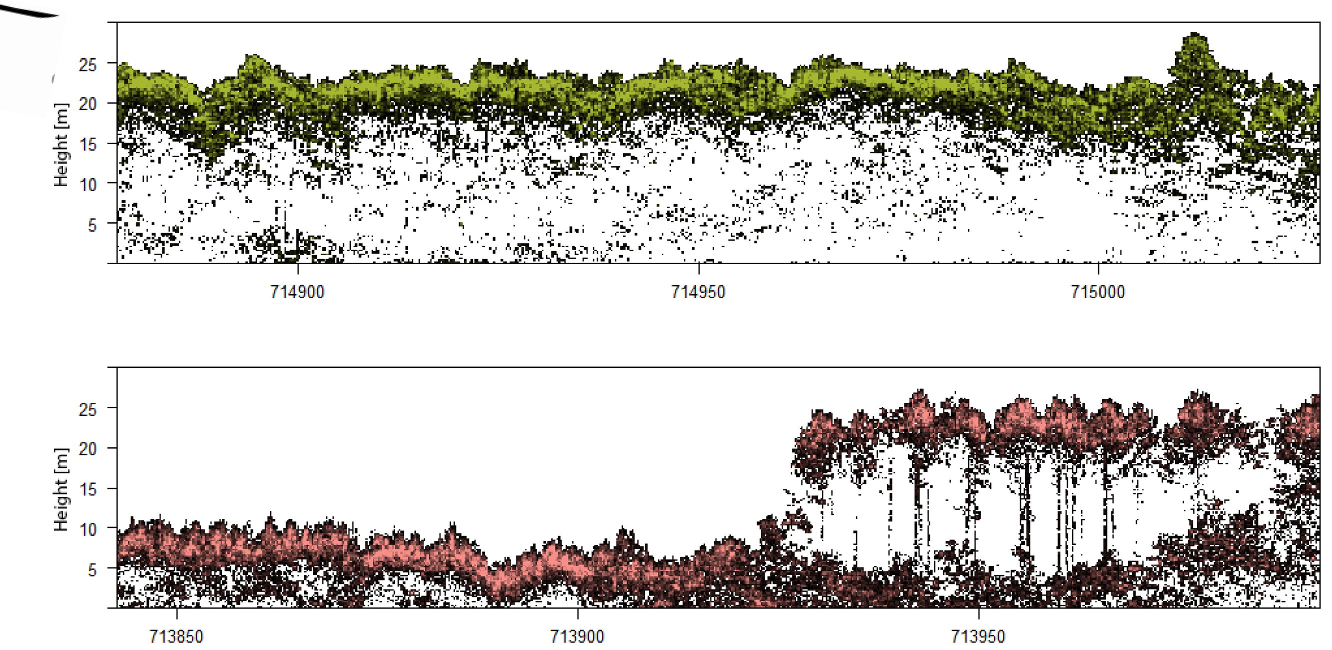


Figure 2. Management practices and frequency of occurrence

The Solution

- 9 EC flux towers deployed in forested sites within the 10 x 10 km **CHEESEHEAD19** field campaign domain in Northern Wisconsin, USA
- EC surface-atmosphere carbon and water fluxes paired with LiDAR-derived forest SC metrics to connect forest structure and function
- Structural Equation Modeling (SEM) to explore mechanistic relationships between SC metrics and GPP, and test mediation effects



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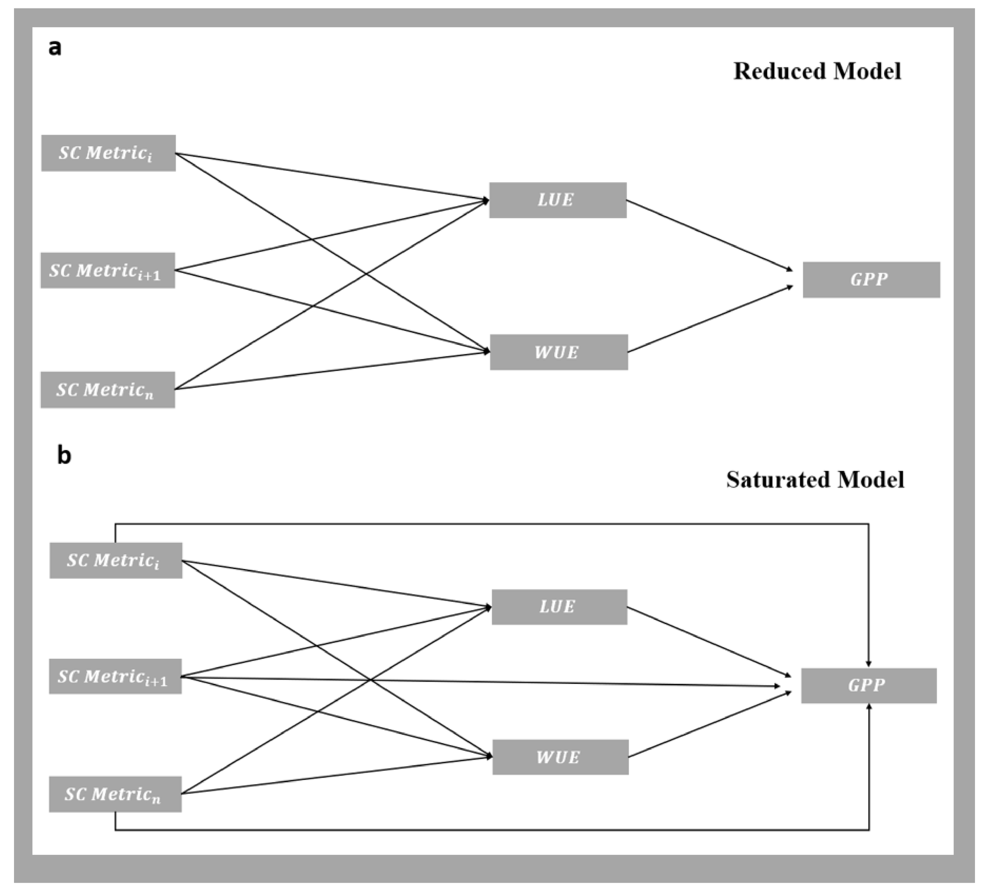
SC metrics affect GPP both directly & indirectly through LUE & WUE

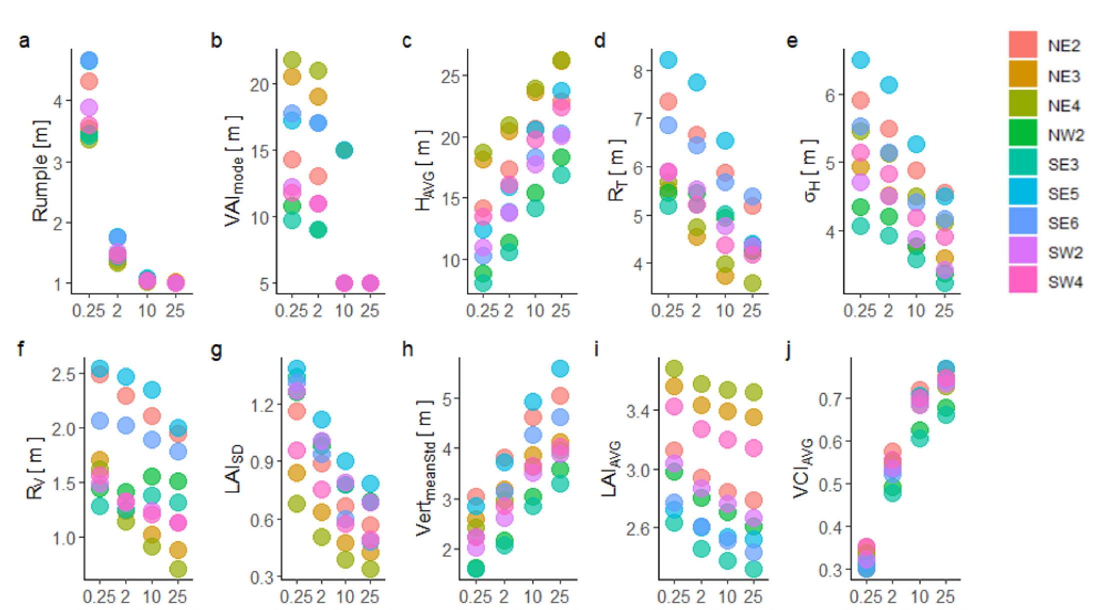


Restricts SC metrics to influencing GPP indirectly through LUE & WUE

Structural Complexity

Scale of metric calculation significantly impacts metric values, as well as which metrics are included in the best fit model

Figure 3. SC metric values at each of the four calculation resolutions: 0.25 m, 2 m, 10 m, and 25 m



Structure-Function Relationship

- Positive mechanistic relationship exists between SC and productivity in mixed temperate forests, BUT relationship is impacted by additional factors such as species diversity and management history
- Relationship is mediated by the effective acquisition and assimilation of both light and water resources, and RUE generally is enhanced by increasing SC
- Water use efficiency (WUE) is a stronger driver of GPP (330%) as well as mediator of the relationship between SC and GPP than light use efficiency (LUE)

Disturbance Impacts

- Sites with intensive disturbance had lower levels of RUE and productivity, sites with moderate management had high levels of complexity and productivity
- Even with shared climatic and environmental conditions, differences in management, disturbance, and species diversity result in variability in exchanges of CO_2.

Key Takeaways

1. Vertical heterogeneity metrics (specifically VCI_{AVG}) are the most influential productivity drivers for temperate forests with a high degree of heterogeneity
2. The structure-function relationship is mediated by RUE, with water use efficiency both the stronger mediator and driver of productivity
3. The mechanistic forest structure-function relationship differs depending upon SC metric calculation resolutions

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