

# Understanding Time-Lagged Causal Effects of Environmental Drivers on Vegetation

## Carbon Uptake

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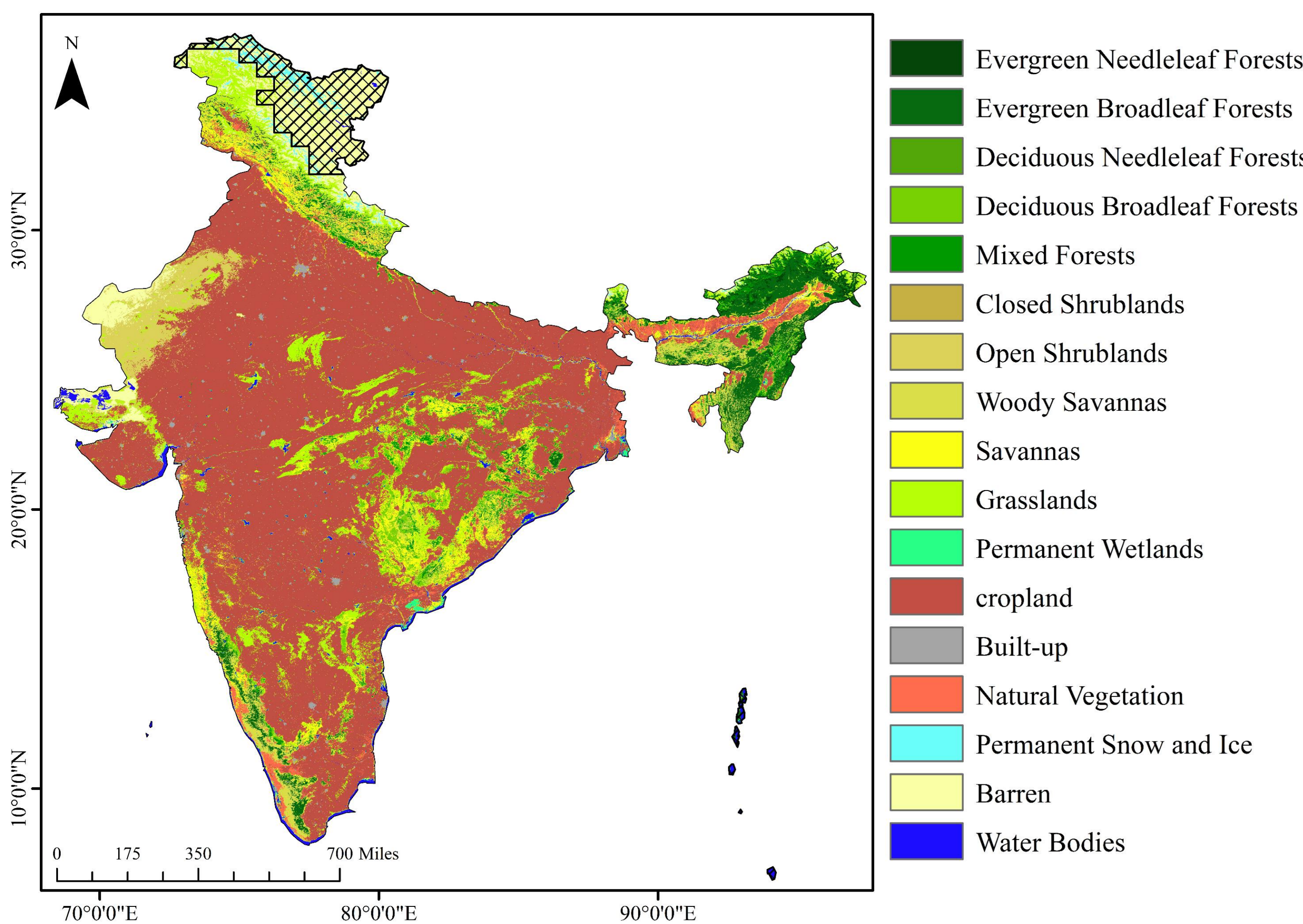
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### Introduction:

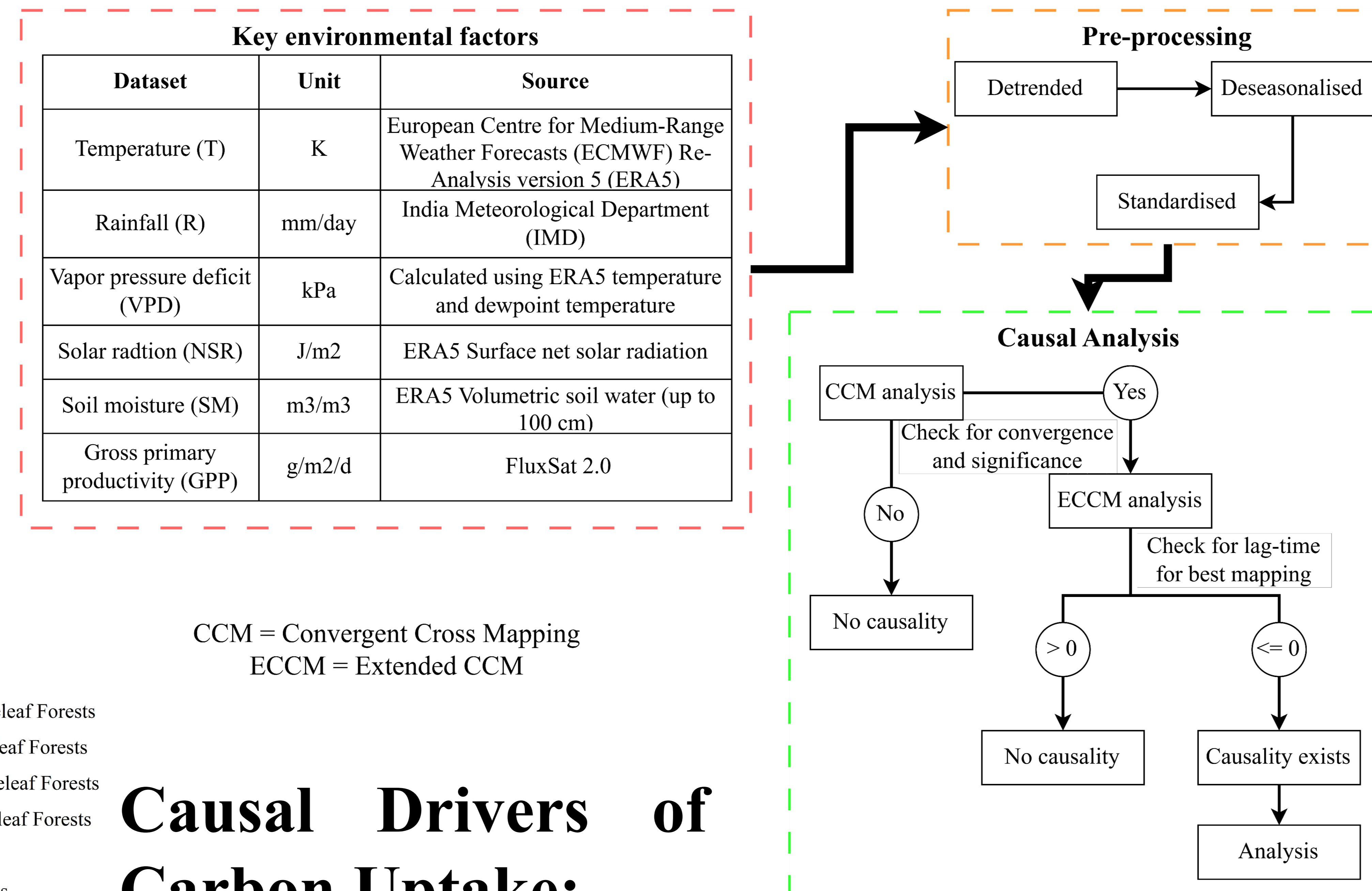
The rise in atmospheric carbon dioxide (CO<sub>2</sub>) is a principal catalyst of global warming, exacerbating hydrological extremes globally. Consequently, enhancing vegetation carbon uptake or sequestration has become essential in conjunction with emission reductions. Nonetheless, the association between environmental variables and carbon uptake is imperfectly interpreted, as conventional correlation and regression techniques fail to elucidate genuine connections. This research overcomes this deficiency by employing causal inference techniques, particularly Convergent Cross Mapping (CCM) (Sugihara et al., 2012).

### Study Area:



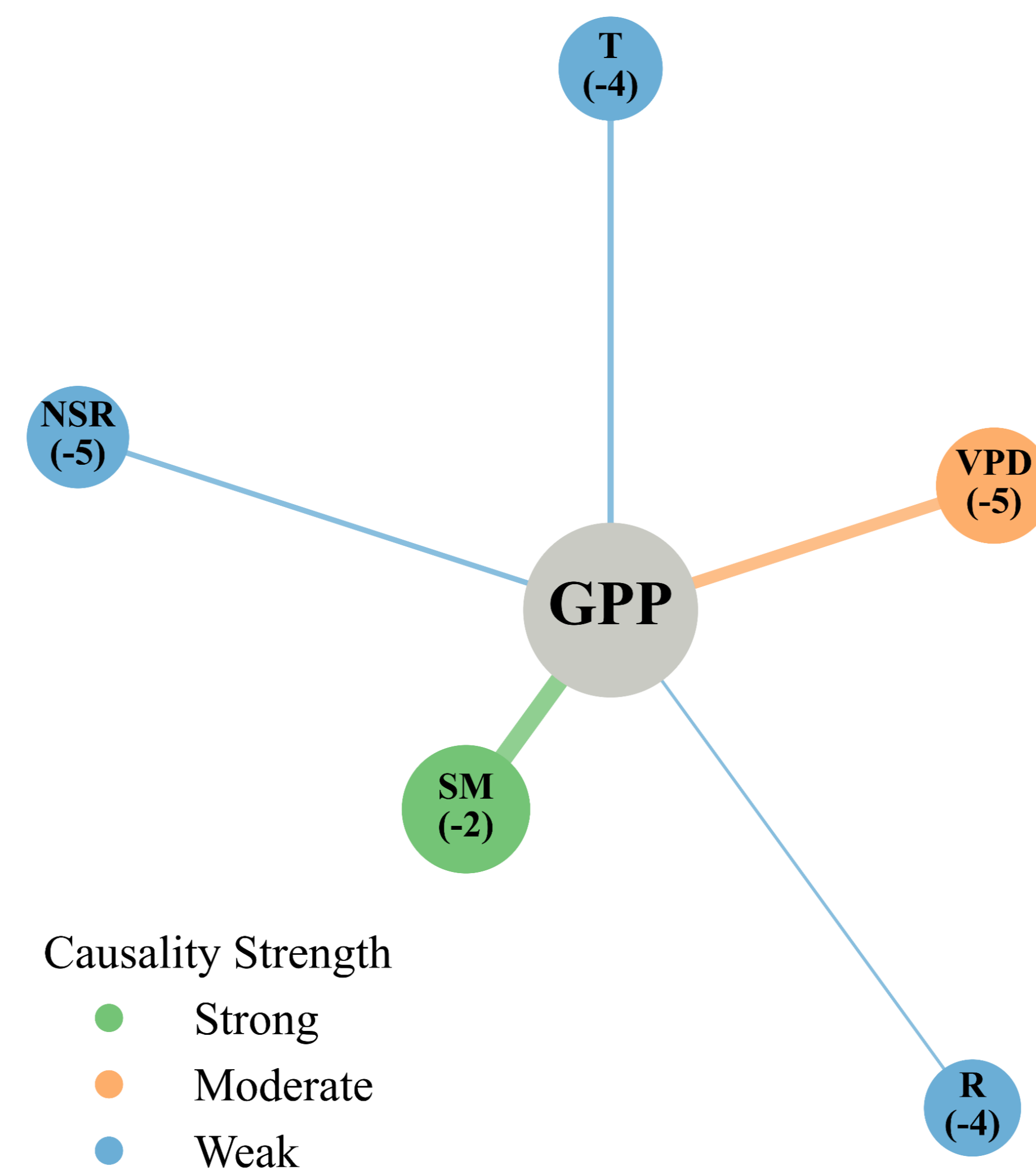
• Root-zone SM exhibits the strongest causal relationship with GPP in typical Indian conditions, as India's land area is predominantly comprised of cropland characterized by high root density, primarily concentrated in the upper soil layers.

### Methodology:



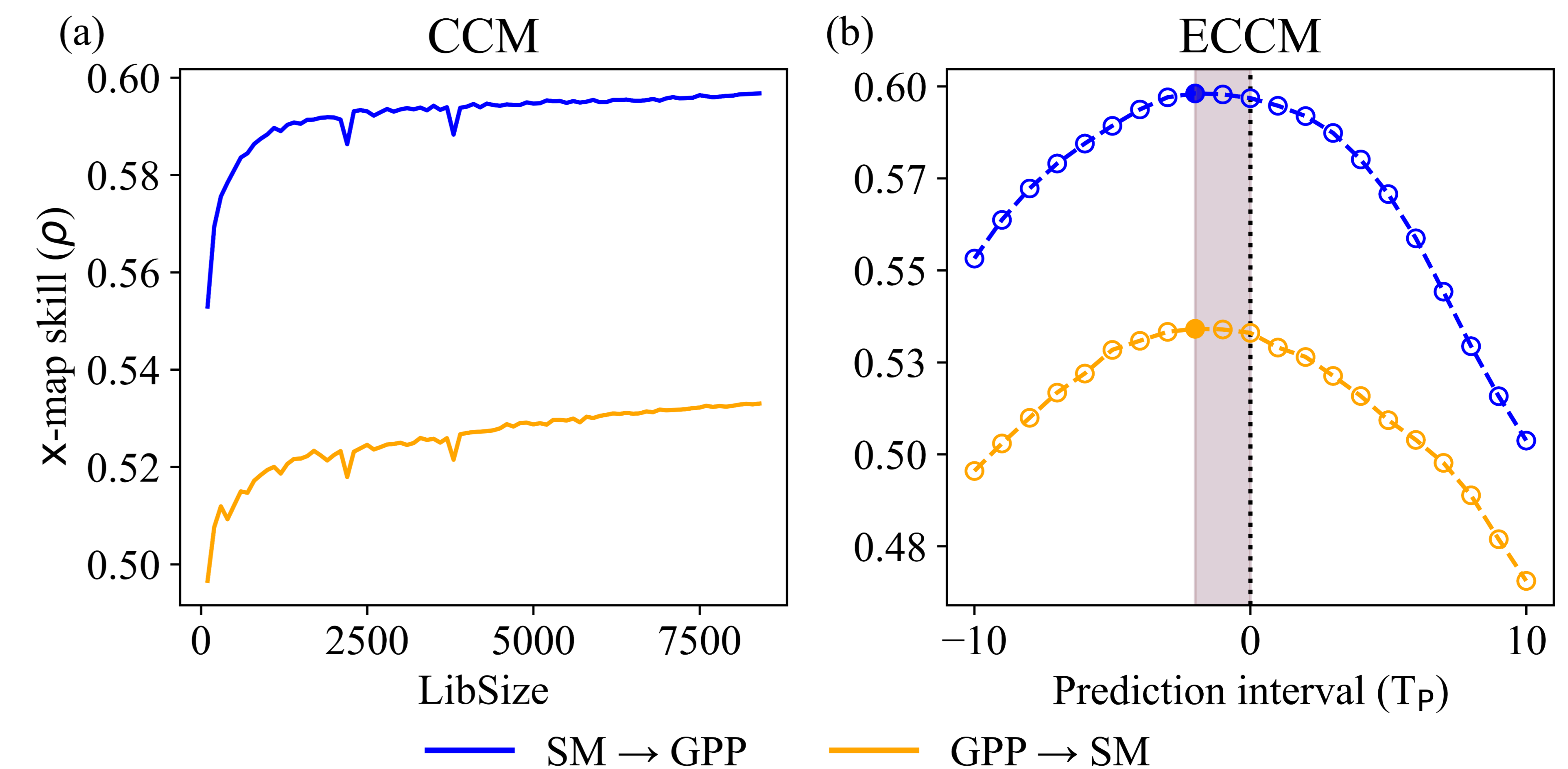
CCM = Convergent Cross Mapping  
ECCM = Extended CCM

### Causal Drivers of Carbon Uptake:

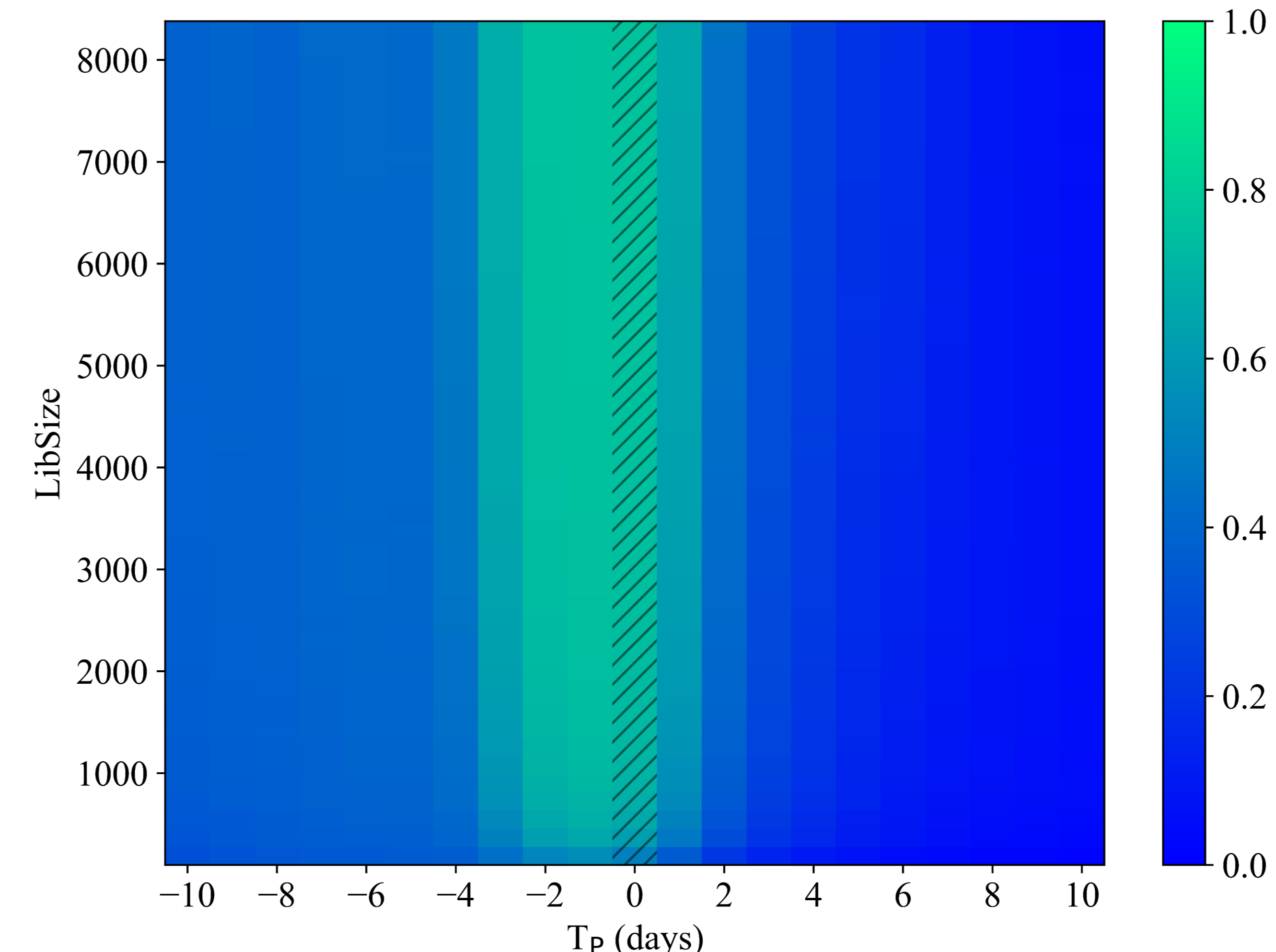


### Soil Moisture ↔ GPP:

- GPP also exhibits a significant reverse causal relationship with root-zone SM, which has an identical lag time of 2 days, underscoring the effective plant-soil hydrological dynamics in average Indian scenarios.
- The increased GPP or photosynthesis generally augments transpiration via heightened stomatal conductance, leading to a reduction in root-zone soil moisture.



### Indirect Rainfall Control on GPP:



- The link between rainfall and GPP is weak, despite the existence of a robust causal relationship between root-zone SM and GPP. It signifies the phenomenon whereby the effects of precipitation are indirectly transmitted through soil moisture.

### Key Limitations:

- The system is predictable and dynamic, rather than wholly random, featuring an underlying state-space attractor or manifold.
- Causality (2001–2023, daily) may vary with temporal span and resolution.

### Reference:

- Sugihara, G., May, R., Ye, H., Hsieh, C. H., Deyle, E., Fogarty, M., & Munch, S. (2012). Detecting causality in complex ecosystems. *science*, 338(6106), 496-500.