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Scale Dependence of Spatial Patterns and Tipping Dynamics in the Boreal Forest

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Escalating climate extremes and environmental pressures are increasingly pushing ecosystems toward regime shifts across the biosphere. Before tipping, however, ecosystems typically lose resilience and exhibit slower recovery from perturbations. This “critical slowing down” behaviour can be quantified through statistical measures to detect early warning signals (EWSs) that arise in timeseries as rising variance, autocorrelation, and skewness. In the spatial domain, the emergence of regular vegetation patterns, known as Turing patterns, has been proposed as a spatial EWS that, along with increasing spatial variability, is interpreted as a hallmark of an approaching critical transition. Nonetheless, a broader gradual spatial reorganisation may instead reflect an ecosystems potential to avoid abrupt collapse by undergoing a Turing bifurcation, experiencing progressive changes in resilience while still drifting towards a less desirable alternative regime. These contradictory theories of what EWSs mean for ecosystems make it crucial to assess whether spatial variability in vegetation emerges as a distinctive sign of an ecosystems’ change in resilience following non-catastrophic shifts. We apply a theoretically grounded framework that links alternative tipping archetypes, such as fold and Turing bifurcations, to expected signatures in both temporal and spatial indicators. By comparing the observed multiscale spatiotemporal patterns with the expectations of different tipping archetypes, we aim to disentangle the scale dependence of tipping dynamics to identify the dominant forcing-response mechanisms operating in complex terrestrial ecosystems. Among these, the Canadian boreal forest stands as a crucial carbon stock exposed to rapid and pronounced warming that renders it vulnerable to structural and compositional transformation. Monitoring it is therefore essential to improve our understanding of the underlying physical mechanisms driving vegetation dynamics and addressing the potential impacts on the ecosystem services they provide if transitioning into degraded states. To achieve this, satellite derived vegetation indices were employed to quantify spatial patterns across multiple resolutions, using hexagonal discrete global grids to characterise vegetation changes in resilience and spatial structure through time. Within a case study region in northern Quebec, the boreal forest exhibited a greening trend from 1984 to 2022 evidenced by an increasing mean of the vegetation indices across scales, but, with an overall decreasing trend in spatial autocorrelation and contrasting trends in spatial variance throughout the region. The observed trends were predominantly prominent at the forest community scales, suggesting a potential scale dependence of the operating tipping archetype and its associated EWS metrics. Datasets on climatic drivers and catastrophic disturbances, including wildfires, droughts, pathogen, and insect

outbreaks, are further incorporated to distinguish exogenous forcing from endogenous ecosystem responses and feedbacks. Identifying these could elucidate whether gradual spatial reorganisation or an impending critical transition in vegetation is occurring. The outcomes could further provide actionable insights to support and improve the management, restoration, and mitigation strategies for forested ecosystems under accelerating climate change.