Characterizing urban vegetation carbon and water flux dynamics using multiscale wavelet phase-lag relationships

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Understanding the temporal dynamics of ecosystem carbon and water exchange in urban vegetation is essential for characterizing the unique environmental conditions of urban areas. Here we combine wavelet coherence and phase-lag diagnostics to investigate how Gross Primary Productivity (GPP), soil respiration (Rs), and evapotranspiration (LE) respond to environmental drivers across multiple time scales. We examined GPP–Rs to quantify the time lag in significant regions of the wavelet domain. A robust and scale-specific pattern indicates a time lag response of Rs to GPP of 39.4 hours (≈1.6 days), with coherence of ~0.75, showing that medium-term adjustments in photosynthesis propagate to belowground respiration with this time delay. These results support a substrate-driven mechanism where canopy-level carbon assimilation leads root and microbial respiration at sub-monthly scales. To contextualize the carbon-cycle dynamics within ecosystem energy and water regulation, we analyzed wavelet coherence between LE and its primary environmental drivers such as solar radiation (Rn), vapor pressure deficit (VPD) and soil water content (SWC). LE–Rn coherence was extremely strong at sub-daily and daily scales, confirming that evapotranspiration is predominantly energy-limited. LE–VPD coherence exhibited additional mid-season enhancement at 4–16-day scales, reflecting periods where atmospheric demand strongly modulates canopy conductance. In contrast, LE–SWC coherence intensified at 8–32-day scales, especially late in the season, revealing a transition toward soil-moisture limitation under prolonged drying conditions. Together, these findings show that ecosystem carbon and water fluxes exhibit distinct but complementary scale-dependent controls: GPP leads Rs at medium time scales due to carbon allocation dynamics, while LE shows a transitions from energy demand to moisture-limitation as temporal scale increases. This multi-scale structure highlights the importance of sub-monthly processes in shaping ecosystem responses to climate variability.