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Seasonal root dynamics and satellite-derived canopy responses in full-sun and agroforestry coffee systems in Costa Rica

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Abstract

Climate variability increasingly challenges coffee production, creating a need for management systems that enhance resilience to changing environmental conditions. Agroforestry systems are often promoted as a climate-resilient alternative to full-sun coffee cultivation, yet knowledge of seasonal root dynamics and their relationship with aboveground canopy responses remains limited.

This study investigated the spatial and seasonal dynamics of coffee root length density (RLD) in full-sun and agroforestry systems in the Western Central Valley of Costa Rica and examined their relationship with canopy responses derived from Sentinel-2 vegetation indices. Root measurements were conducted across seasons and soil depths, while satellite imagery was used to monitor canopy condition and stress responses. Both production systems exhibited pronounced seasonal changes in RLD, with a marked decline during the transition from the dry to the rainy season followed by recovery during the rainy season. However, recovery patterns differed between systems. In the full-sun system, canopy greenness recovered rapidly after the onset of rainfall, whereas root recovery occurred more gradually. In contrast, the agroforestry system showed a rapid recovery of RLD shortly after the beginning of the rainy season, while canopy recovery was slower. Spatial differences were also observed: coffee plants in the agroforestry system exhibited significantly higher RLD in the upper soil layers (0–30 cm) than those in the full-sun system, indicating contrasting belowground resource acquisition patterns.

These findings demonstrate that aboveground and belowground responses to seasonal climatic variability may occur asynchronously and that their temporal relationships differ between coffee production systems. Integrating field-based root observations with satellite-derived vegetation indices provided insights into whole-plant responses that would not have been apparent from belowground measurements alone. Such knowledge can support the development of more climate-resilient coffee production strategies and improve resource-use efficiency through better alignment of fertiliser timing and placement with temporal and spatial root dynamics.

Keywords: Coffee agroforestry, Costa Rica, NDVI, root length density, seasonal dynamics, Sentinel−2, vertical root distribution

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