

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

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Introduction and Objectives

Coffee agroforestry systems [AFS] are often promoted as a climate-resilient alternative to full-sun cultivation [FSS]. However, the spatial and seasonal dynamics of coffee root systems under shade trees remain poorly understood, particularly in relation to aboveground canopy responses.

Therefore, this study aimed to:

1. Characterise the spatial distribution of coffee root length density [RLD] in AFS and FSS.
2. Assess seasonal dynamics of coffee roots and canopy.
3. Explore the relationship between belowground root dynamics and aboveground canopy responses.

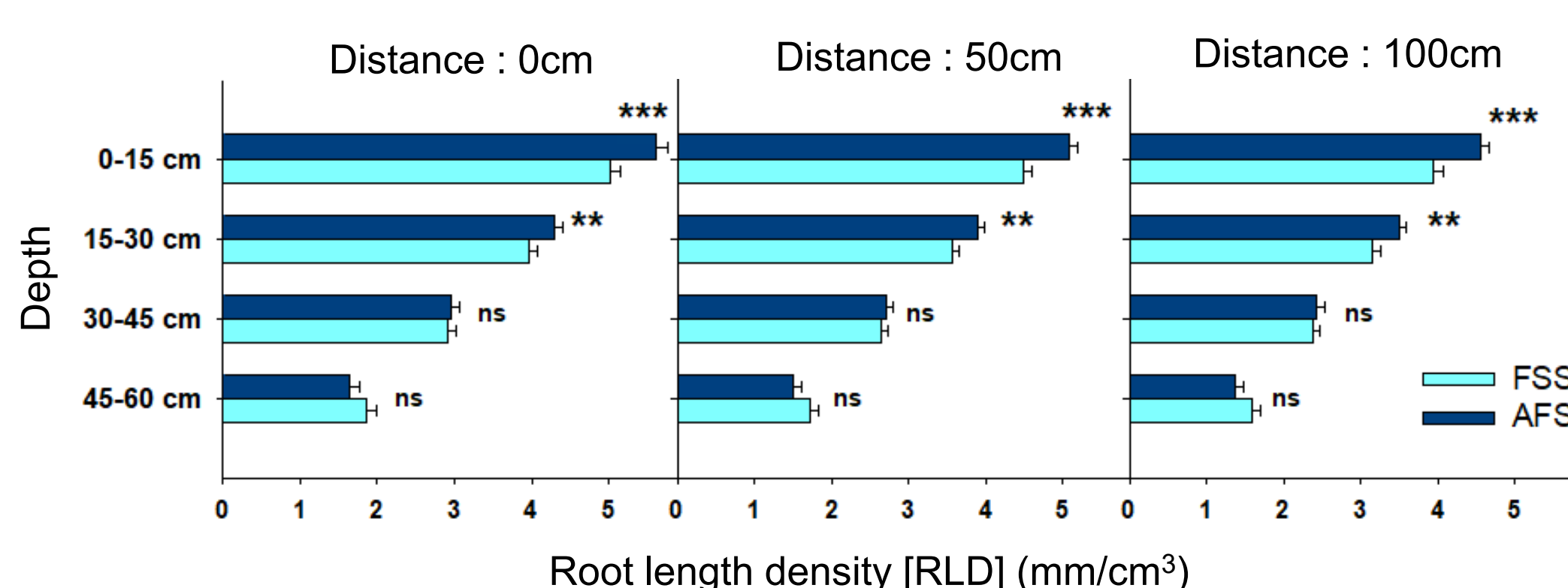


Conclusions

- Coffee root systems are highly dynamic throughout the season, showing a distinct reduction with the onset of rainy season.
- Agroforestry system exhibited significantly higher coffee root density at shallower layers
- During the rainy season, agroforestry showed contrasting recovery timing: rapid root recovery but delayed canopy recovery compared with full-sun coffee.

Results and Discussion

Spatial root distribution



Effects	p-value
Production system	0.003**
Depth	< 0.001***
Distance	< 0.001***
Production system × Depth	0.004**
Depth × Distance	0.019*

Figure 1: Root length density [RLD] of coffee agroforestry [AFS] and full-sun system [FSS] at across soil depths and distances from the coffee stem. The table summarises significant effects of production system, depth, distance and their interactions of a Linear Mixed Model. Asterisks indicate significant differences between the production systems within the same depth and distance (ns: non-significant, *p < 0.05; **p < 0.01; ***p < 0.001).

- RLD decreased significantly with distance from the coffee stem and soil depth.
- AFS had significantly higher RLD in shallow soil layers than FSS.

Functional implications

Greater shallow-root concentration in AFS may indicate stronger reliance on upper-soil resources, potentially increasing vulnerability to water limitation during prolonged dry periods.

Seasonal dynamics

Belowground - Root dynamics (RLD)

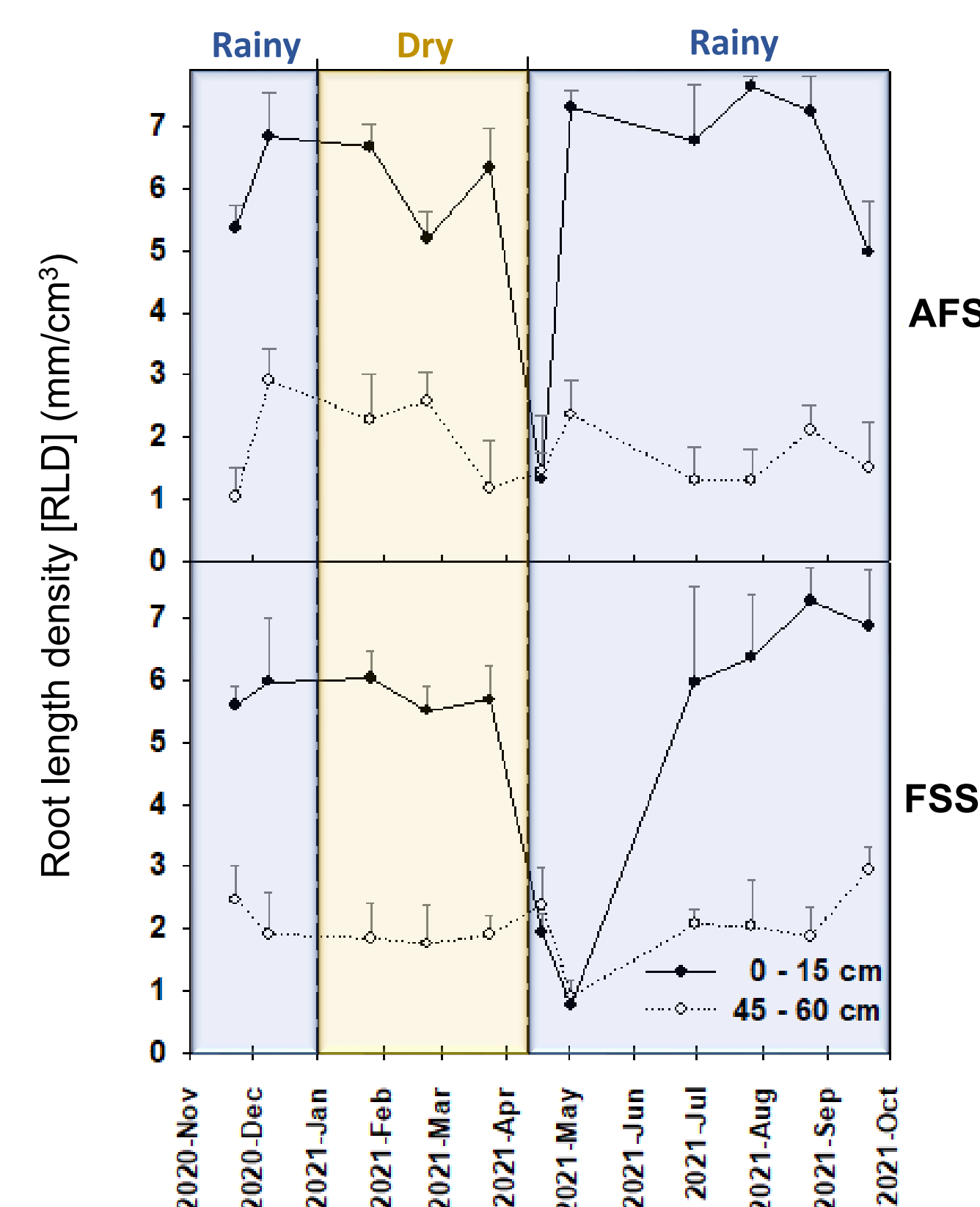


Figure 2: Seasonal variation in coffee root length density [RLD] at 0-15 and 45-60 cm soil depths in agroforestry system [AFS], above, and coffee full-sun system [FSS], below, at 0 cm distance from the stem. Background shading indicates rainy and dry seasons.

- Strong seasonal variation in RLD, particularly in shallow soil layers.
- Sharp RLD decline at rainy-season onset in both systems.
- Earlier RLD recovery in AFS than FSS during the rainy season.

Aboveground - Canopy dynamics (NDVI)

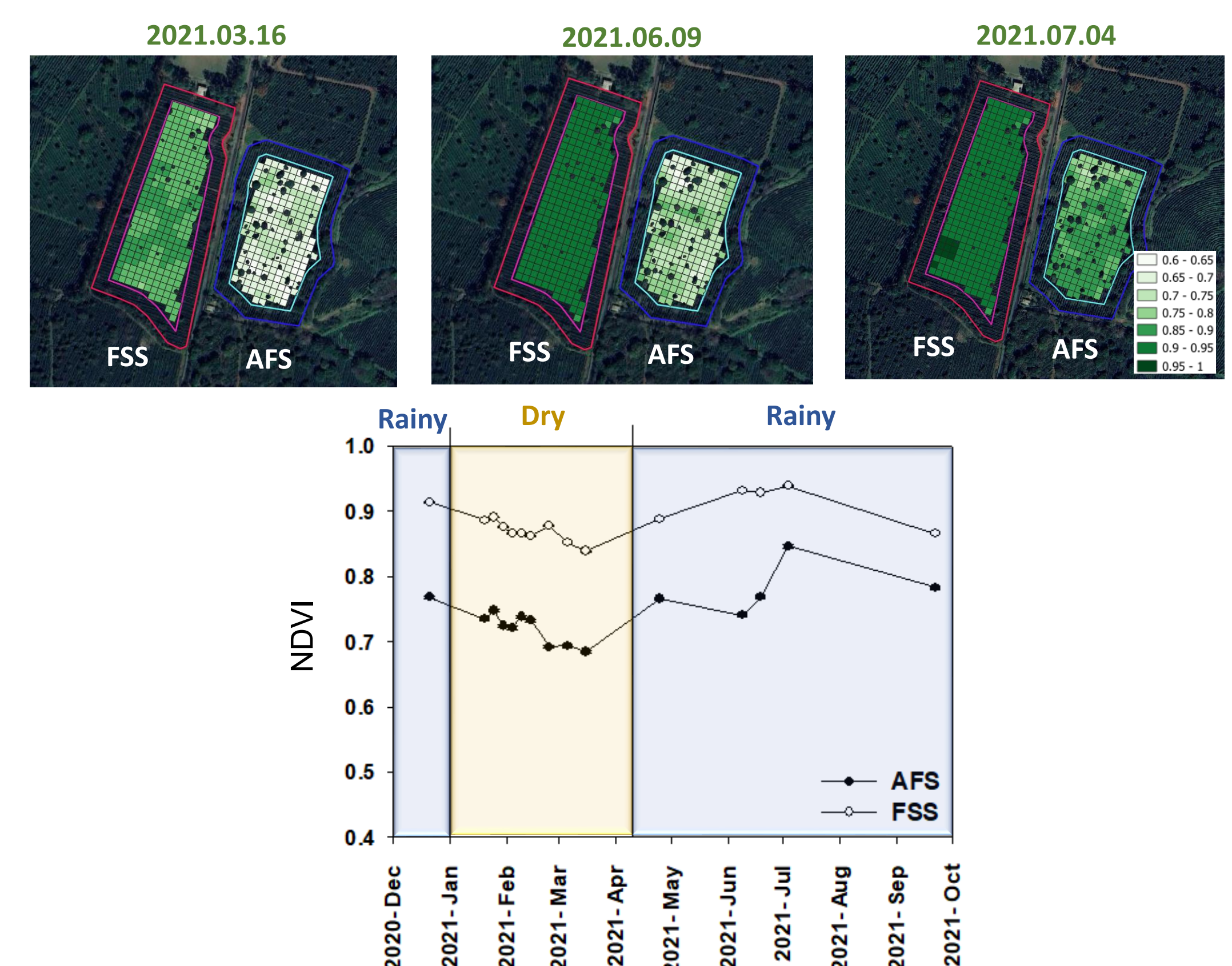


Figure 3: Spatial and seasonal variation in coffee NDVI in agroforestry [AFS] and full-sun systems [FSS]. Maps show NDVI distribution at selected dates, while the time series shows mean NDVI across the study period. Background shading indicates rainy and dry seasons.

- FSS maintained higher NDVI than AFS throughout the observation period
- Canopy greenness recovered earlier in FSS, while recovery was delayed in AFS.

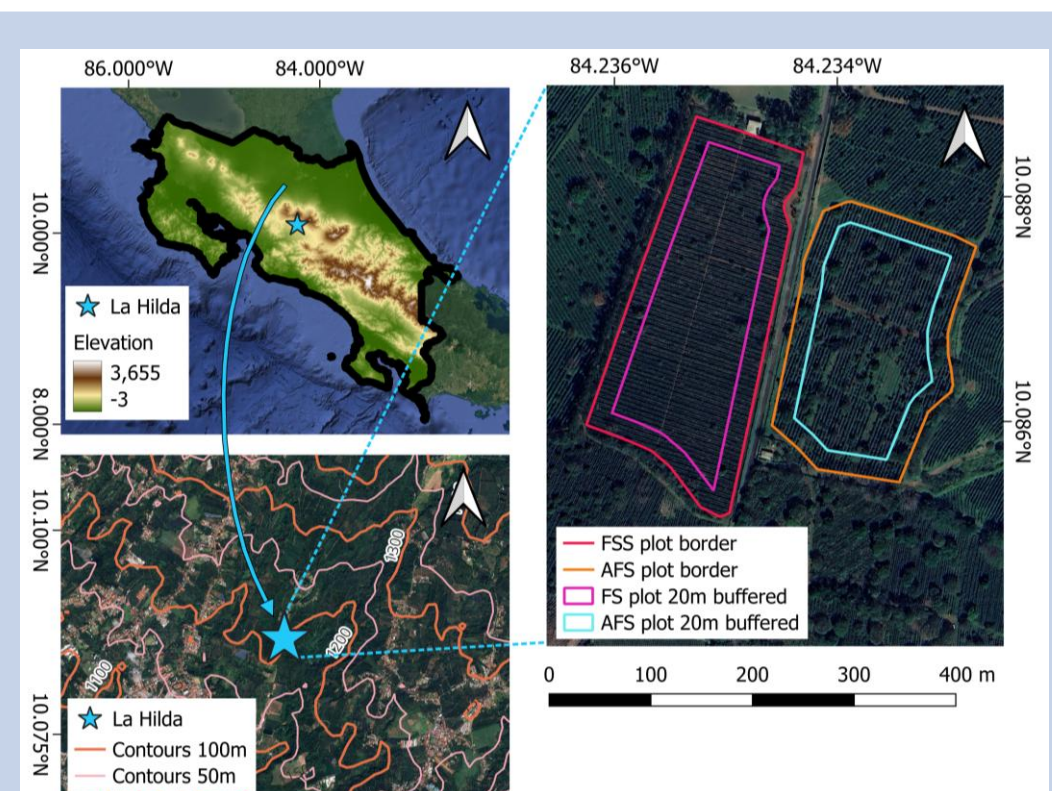
Contrasting below- and aboveground recovery during rainy season

AFS: Rapid **root** recovery → Delayed **canopy** recovery
 FSS: Rapid **canopy** recovery → Delayed **root** recovery
 → Below- and aboveground responses to seasonal change were not synchronous and differed between production systems.

Materials and Methods

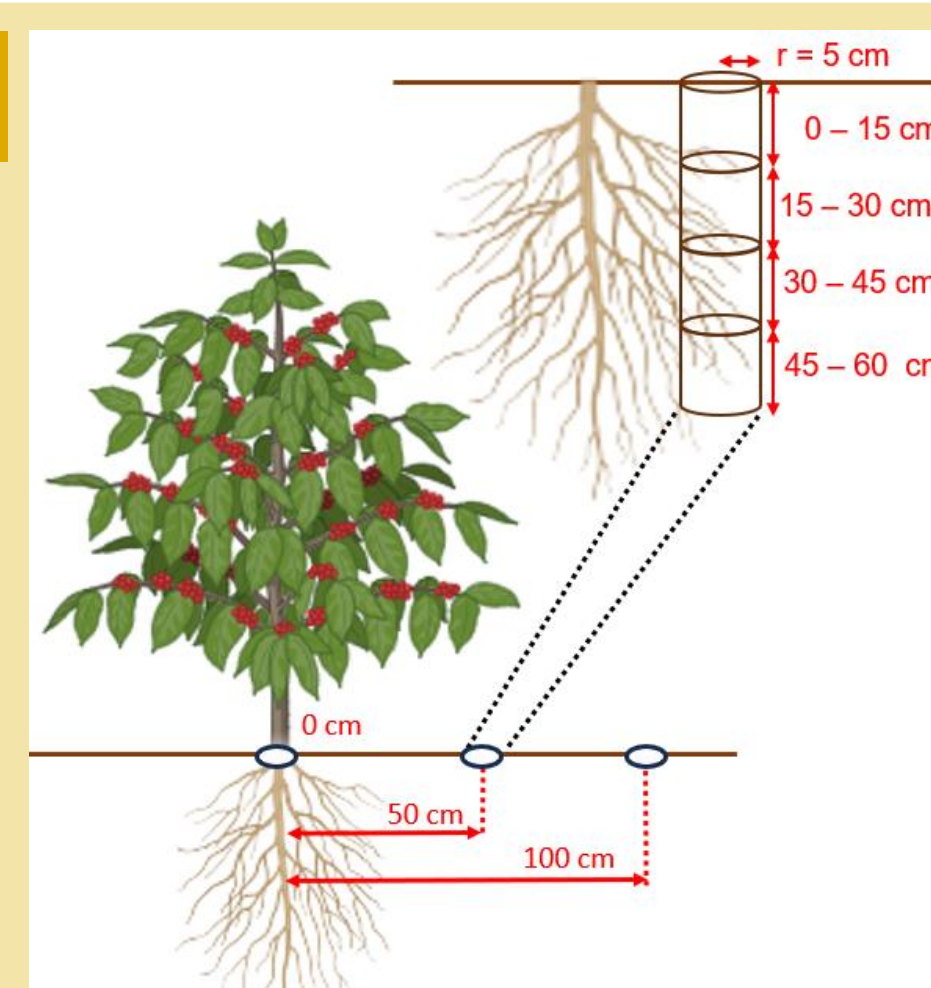
1. Study site

The field trial was conducted at La Hilda Farm in the Western Central Valley of Costa Rica with (1210 m a.s.l.) from 2020/11 to 2021/09, comparing agroforestry (AFS) and full-sun coffee systems (FSS).



2. Root sampling

Soil cores were collected monthly from five randomly selected coffee trees per plot at five sampling positions (0, 50 and 100 cm from the stem) and four soil depths (0–15, 15–30, 30–45 and 45–60 cm). Root length was quantified using WinRHIZO and expressed as root length density (RLD).



3. Sentinel-2 based remote sensing

NDVI was derived from Sentinel-2 Red and NIR bands for 35 cloud-free acquisition dates. A 20 m buffer from field edges and masking of shade-tree canopies were applied to minimise interference with coffee canopy signals.

