

Gijs van den Dool<sup>1</sup>, Sacha Malka<sup>2</sup>, Joseph A. Paintsil<sup>2</sup>, and Ellie Jones<sup>3</sup>  
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## Introduction

Monitoring cocoa within complex West African agroforestry remains an EO challenge; in this study we use high-dimensional hyperspectral data fused with phenological embeddings to resolve sub-pixel cocoa under forest canopy.

**The Global Context:** West Africa produces most of the world's cocoa, often within complex tropical agroforestry systems.

**The Regulatory Push:** The EU Deforestation Regulation (EUDR) now mandates strict, farm-level verification to ensure cocoa is "deforestation-free".

**The Mapping Bottleneck:** Standard multispectral imagery (like Sentinel-2) struggles to distinguish cocoa from native forest shade canopies due to nearly identical spectral signatures.

**The Technological Gap:** While TESSERA phenological embeddings provide structural insights, they are often insufficient alone for high-fidelity mapping in dense landscapes.

**Our Hypothesis:** Integrating Wyvern's high-resolution, 31-band hyperspectral imagery through latent space fusion will provide the discriminative "spectral fingerprints" needed to resolve sub-pixel cocoa abundance.

## Cocoa in West Africa



As the world's largest cocoa producer, Côte d'Ivoire faces urgent pressure to meet new EU Deforestation Regulation (EUDR) requirements for traceable sourcing.

**Abeya** is an AI-powered network that reconnects smallholders directly with global manufacturers by establishing traceability at the farm level. By mapping farms on-site and monitoring via satellite, Abeya removes intermediaries and improves farmer margins while ensuring verified, compliant supply chains.

For this study, Abeya provided the ground-truth polygons and network data used to calibrate the cocoa endmember models driving the fusion pipeline.

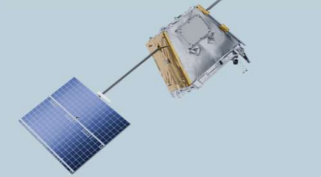
### TESSERA Model

**TESSERA Model:** A geospatial Foundation Model representing 128-dimensional phenological embeddings that capture the structural dynamics of the canopy over time; the model learns by comparing random temporal view.



### Wyvern Imagery

**Wyvern Dragonette-002/004:** Provides high-resolution hyperspectral imagery with 31 bands, specifically targeting the VNIR and visible domains to resolve sub-pixel biochemical signals. Two images are collected over the period Jan–Mar 2026 to complement the Sentinel 1 & 2 collection used in the TESSERA model.



## Methodology: Scene-Scoped Sensor Fusion Approach

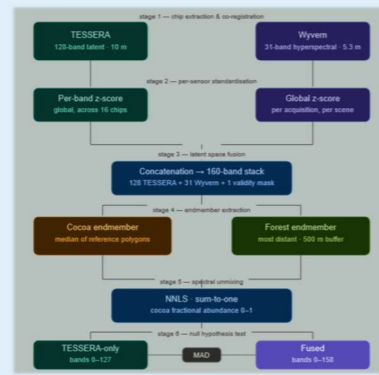


Fig. 1 — Six-stage sensor fusion pipeline

A multi-sensor pipeline combines TESSERA phenological embeddings with Wyvern hyperspectral data by resampling and co-registering the Wyvern images to the 10 m TESSERA grid, derived from the Sentinel-1/2 archive.

Fusing 128-band latent embeddings with 31 hyperspectral reflectance bands enables discrimination of cocoa from spectrally similar forest cover — a distinction that multispectral phenology alone cannot reliably resolve.

Although TESSERA embeddings are class-agnostic, endmember extraction is anchored to reference cocoa polygons (manually sourced monoculture cocoa plots), ensuring the latent space is aligned with the target land-cover class.

## Concatenation: Resolving the Spectral Overlap

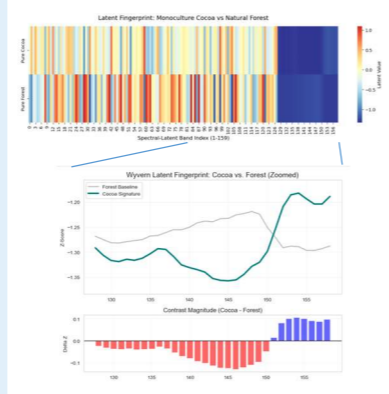
Cocoa and forest are spectrally similar in broadband optical data. To resolve this ambiguity, TESSERA phenological embeddings are concatenated with Wyvern hyperspectral reflectance in a shared 159-band latent space.

In the combined data cube, each 10 m pixel encodes both the phenological dynamics of the canopy (TESSERA, bands 1–128) and its biochemical reflectance signature (Wyvern, bands 129–159).

The latent fingerprint (top) confirms that Wyvern bands (128–159) introduce a consistent cocoa–forest contrast which is more difficult to detect by phenology alone; **Daloa** R4C4 is shown as a representative example, as the pattern is consistent across all tiles in both study sites.

Although, for **Danané** the z-delta is larger for both the TESSERA and Wyvern signal.

Fig. 3 — Latent fingerprint, Daloa site, tile R4C4



## NNLS Unmixing: Scene-Scoped Abundance Estimation

Extracting site-specific endmembers from reference polygons anchors the Non-Negative Least Squares (NNLS) solver to local ecological conditions, enabling the model to resolve the cocoa signal even in high-overlap transition zones.

Parcel-level mean cocoa abundance was compared between TESSERA-only and fused estimates across all reference farm parcels. While Wyvern systematically reduced abundance estimates in **Danané**, with most values falling below the 1:1 line, the results in **Daloa** showed closer agreement, reflecting the broader spectral overlap observed in the PCA (Fig. 4).

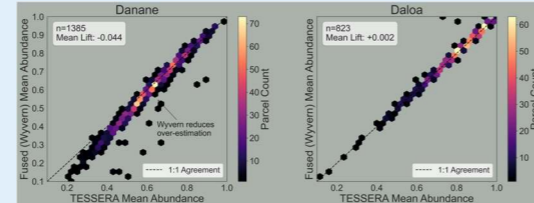


Fig. 5 — Non-Negative Least Squares comparison

## Study Areas

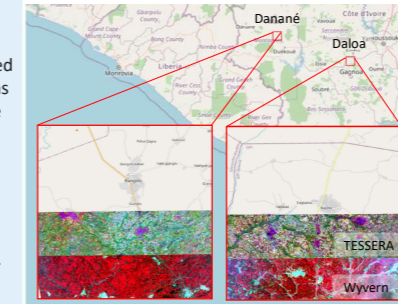
Two sites in Côte d'Ivoire were selected to represent contrasting cocoa agroforestry landscapes.

**Danané**, in the western Tonkpi district, is characterised by a humid tropical climate and dense forest cover, where smallholder farmers cultivate cocoa beneath a complex, multi-layered canopy, or newly established monoculture farms benefitting from converted forest. This intricate structure makes spectral discrimination particularly challenging and dynamic.

**Daloa**, in the central-western Haut-Sassandra region, is one of Côte d'Ivoire's dominant cocoa areas, with a heterogeneous mosaic of cocoa farms, secondary forests, and mixed land cover. The area is undergoing ecological shifts, with increasing drought

These two sites, together, illustrate the ecological diversity and mapping challenges in complex cocoa agroforestry landscapes.

Fig. 2 — Selected Study Locations



## Endmember Construction: Latent Space Separability

To anchor the class-agnostic TESSERA embeddings, endmembers are extracted directly from the fused latent space. Principal Component Analysis (PCA) of the 159-band fused representation demonstrates clear spectral-temporal separation at both study sites.

In **Danané**, a compact and well-separated cocoa cluster (PC1: 29.2% var) enables stable extraction. Conversely, the **Daloa** study site shows a greater overlap with secondary forest (PC1: 19.4% var), indicating increased landscape heterogeneity and underscoring the limitations of hyperspectral enhancement in complex agroforestry environments.

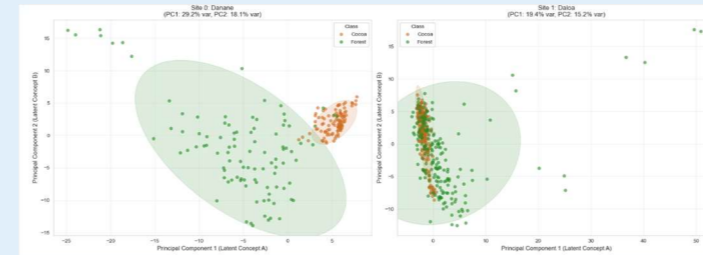


Fig. 4 — PCA comparison

## Sensor Fusion Validation: Three-Model Intercomparison

Three independent remote sensing methods were tested on land parcels to measure the effects of hyperspectral data fusion.

In **Danané**, the models differ the most (Abeya=0.827, TESSERA=0.615, Fused=0.571). The biochemical signature from Wyvern helps distinguish cocoa from similar shade plants, enabling a correction that TESSERA's structural data alone cannot achieve. In **Daloa**, all methods show aligned results (Abeya=0.807, TESSERA=0.790, Fused=0.795).

In areas with mixed cocoa and forest (Fig. 4), the fused data adds little extra signal, suggesting the main challenge lies in the landscape's complexity, not the models themselves.

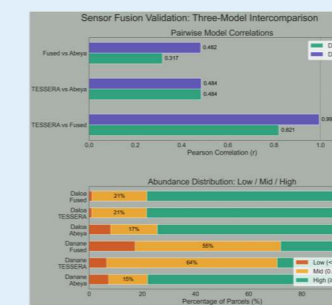


Fig. 6 — Sensor Fusion Validation

## Discussion & Conclusion

**Latent Space Fusion:** A six-stage pipeline combining TESSERA phenological embeddings with Wyvern hyperspectral data successfully encoded both canopy dynamics and biochemical reflectance in a unified 160-band representation, enhancing cocoa–forest separability in latent space.

**Hyperspectral Correction:** Null hypothesis testing confirmed that Wyvern hyperspectral data introduces independent discriminative information beyond phenology alone ( $r=0.821$  in **Danané** vs  $r=0.995$  in **Daloa**), with a consistent downward correction in cocoa abundance estimates observed in **Danané**.

**Scene-Scoped Normalisation:** Independent per-scene normalisation was shown to be essential for preserving within-scene discrimination signal across ecologically diverse landscapes, preventing cross-scene radiometric variability from diluting endmember contrast.

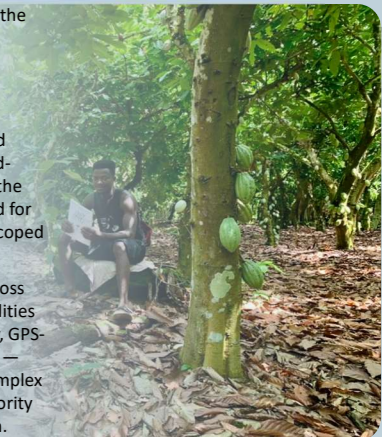
**Operational Scalability:** The scene-scoped fusion framework enables hyperspectral discrimination to be anchored to the global Sentinel-1/2 archive, providing a pathway toward regional cocoa monitoring at the scale required for EUDR compliance.

## Limitations & Future Work

Future iterations will incorporate the NNLS residual band to identify additional land cover classes and extend the pipeline to a full Côte d'Ivoire assessment.

The compression of **Danané** fused estimates into the ambiguous mid-range (55% of parcels vs 15% for the reference model) indicates a need for further investigation into scene-scoped normalisation strategies.

While inter-model agreement across three independent sensing modalities provides a useful validation proxy, GPS-verified parcel-level ground truth — particularly in the ecologically complex **Daloa** landscape — remains a priority for robust independent validation.



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## Authors

<sup>1</sup> Independent Researcher, [gijs.vandendool@gmail.com](mailto:gijs.vandendool@gmail.com) [[www.linkedin.com/in/gvddool/](https://www.linkedin.com/in/gvddool/)]

<sup>2</sup> Abeya, [sacha@abeya.co](mailto:sacha@abeya.co) [[www.abeya.co](http://www.abeya.co)]

<sup>3</sup> Wyvern, [ellie.jones@wyvern.space](mailto:ellie.jones@wyvern.space) [[www.wyvern.space/](http://www.wyvern.space/)]

