Sat4Carbon: Integration of Thermal Remote Sensing and Mechanistic Models for Carbon Flux Quantification in Silvopastoral Ecosystems

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INTRODUCTION

Carbon Cycle Monitoring in Silvopastoral Ecosystems

Silvopastoral ecosystems are recognised as potential carbon sinks, yet their operational quantification remains a methodological challenge. Empirical models fail to capture the dynamic physiological response of vegetation to water stress, while reference flux towers (Eddy Covariance) have limited spatial coverage and high deployment costs.

~30% — of European agricultural lands have been identified as target areas for agroforestry systems with **carbon sequestration**

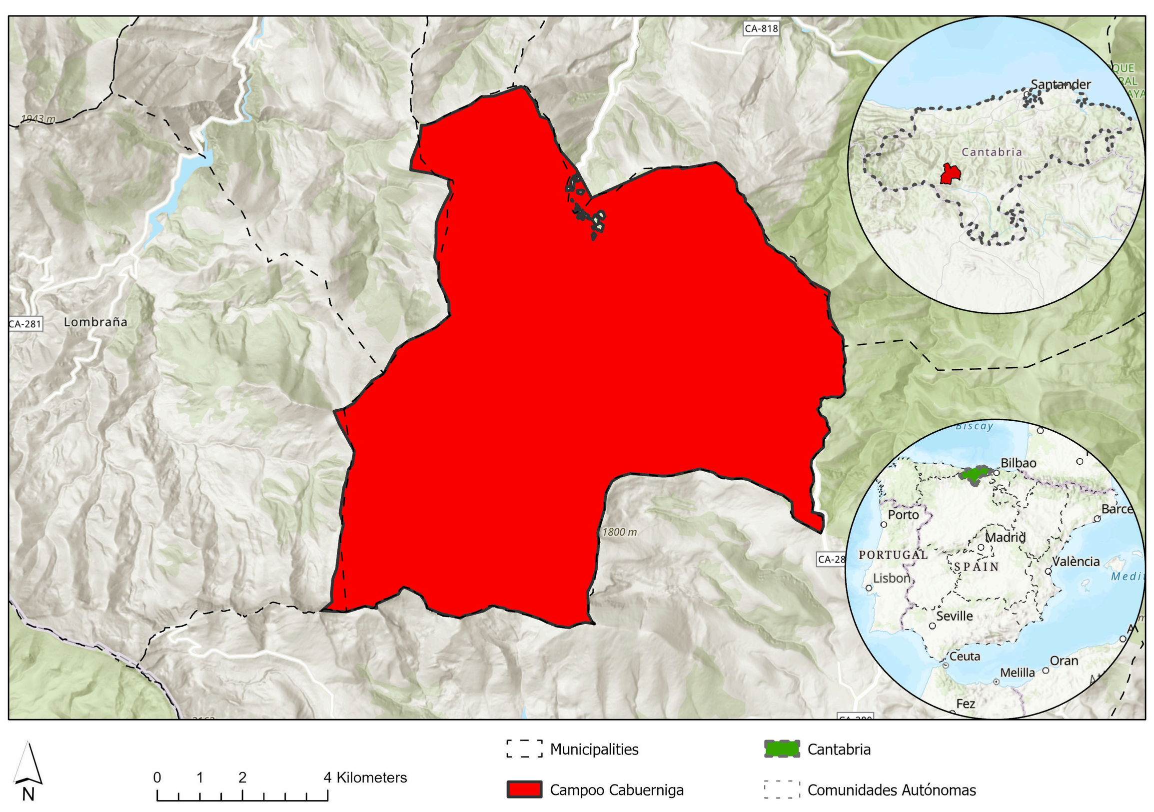
↑ H_2O — **Water stress** significantly alters CO_2 uptake, but traditional empirical models cannot capture this response with sufficient precision

↔ km — **Eddy Covariance towers** are the reference standard but have limited spatial footprint and represent a costly infrastructure

STUDY AREA

Campoo-Cabuérniga MUP - Cantabria, Spain

Location of the study area



~7,000 ha of forest & pasture

4 jointly managing munipalities

METHODOLOGY — WORKFLOW

Integrated Remote Sensing Pipeline

Fully operational, scalable approach using Copernicus data — no field calibration required

INPUT	MODEL 1	LINK	MODEL 2	OUTPUT
Satellite Data Sentinel- 2/3 Landsat TIRS ERA5	**TSEB Energy Balance** LST ET partition → g_s	**g_s** Stomatal conductance	**Farquhar FvCB** C3 plants g → A_{sn} Biochemical	**Carbon Fluxes** GPP daily GPP annual NEE

Key coupling mechanism: stomatal conductance (g_s) derived from TSEB acts as the physiological link regulating CO_2 diffusion into the mesophyll — connecting the energy balance to the biochemical photosynthesis model

MODEL 1 — ENERGY BALANCE

TSEB: Two-Source Energy Balance

From land surface temperature to stomatal conductance

01 Surface Temperature Partitioning
LST from Sentinel-3 (SLSTR) is decomposed into soil and vegetation components using the two-source TSEB model

02 Latent Heat Flux Estimation
Actual evapotranspiration (ET) is obtained and partitioned into transpiration (T) and evaporation (E) using energy balance closure

03 Stomatal Conductance as Physiological Proxy
g_s is derived from canopy transpiration — it captures water stress that regulates stomatal aperture and, ultimately, CO_2 uptake

MODEL 2 — PHOTOSYNTHESIS

Farquhar-von Caemmerer-Berry (FvCB) Model

From g_s to carbon fixation: mechanistic biochemical approach for C3 plants

01 Stomatal Conductance Input $(g)_s$
Derived from TSEB; regulates CO_2 diffusion into the leaf mesophyll and encodes the plant water-stress signal

02 Biochemical Assimilation Rate
FvCB limits net assimilation by Rubisco carboxylation (V_{cmax}) or electron transport (J_{max}), depending on thermal and water conditions

03 Spatial & Temporal Scaling
Daily and annual fluxes integrated at 20 m pixel resolution using Sentinel-2 LAI; gap-filling and temporal aggregation applied

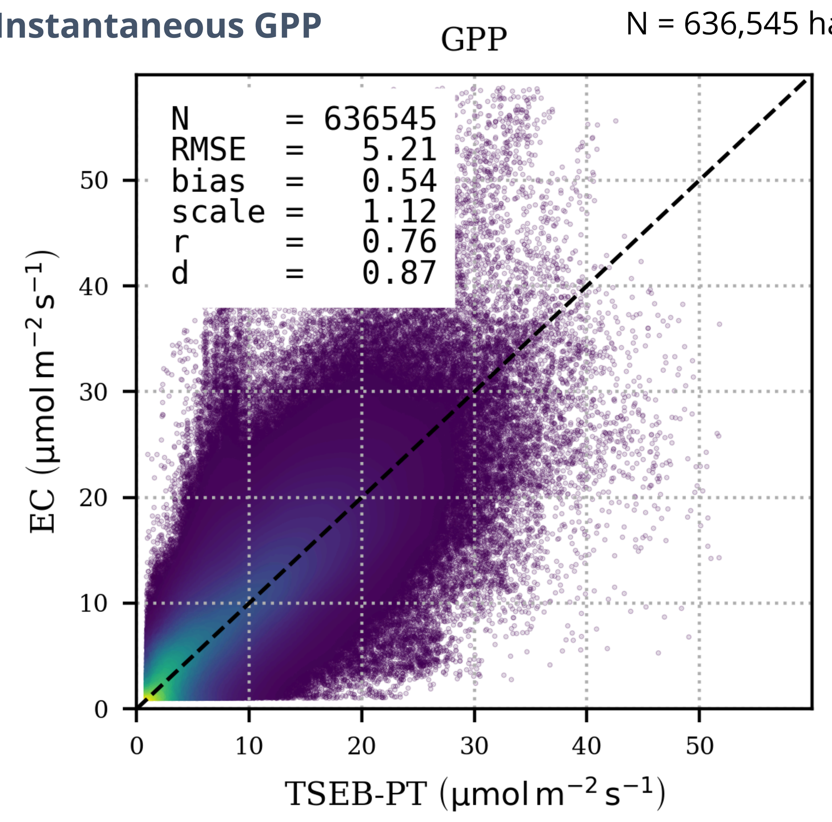
GPP Gross Primary Production g C m⁻² day⁻¹ / year⁻¹

NEE Net Ecosystem Exchange Source / Sink classification

VALIDATION — ICOS NETWORK

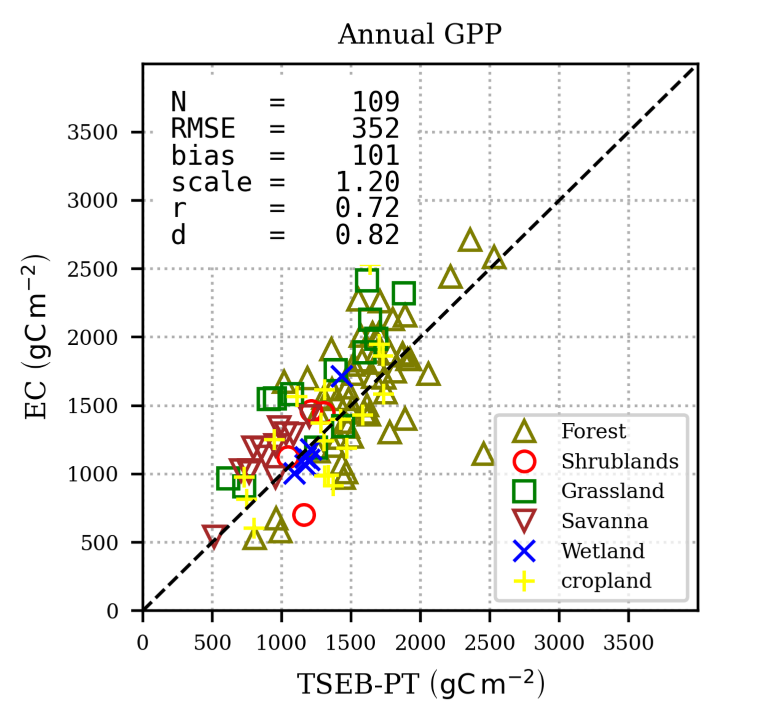
Warm Winter 2020 — European Eddy Covariance Network
No site-level empirical calibration — fully transferable approach across European biomes

Instantaneous GPP N = 636,545 half-hourly obs.



0.76 r
5.21 RMSE
0.54 bias
0.87 d

Annual GPP N = 109 site-years · 6 ecosystem types.



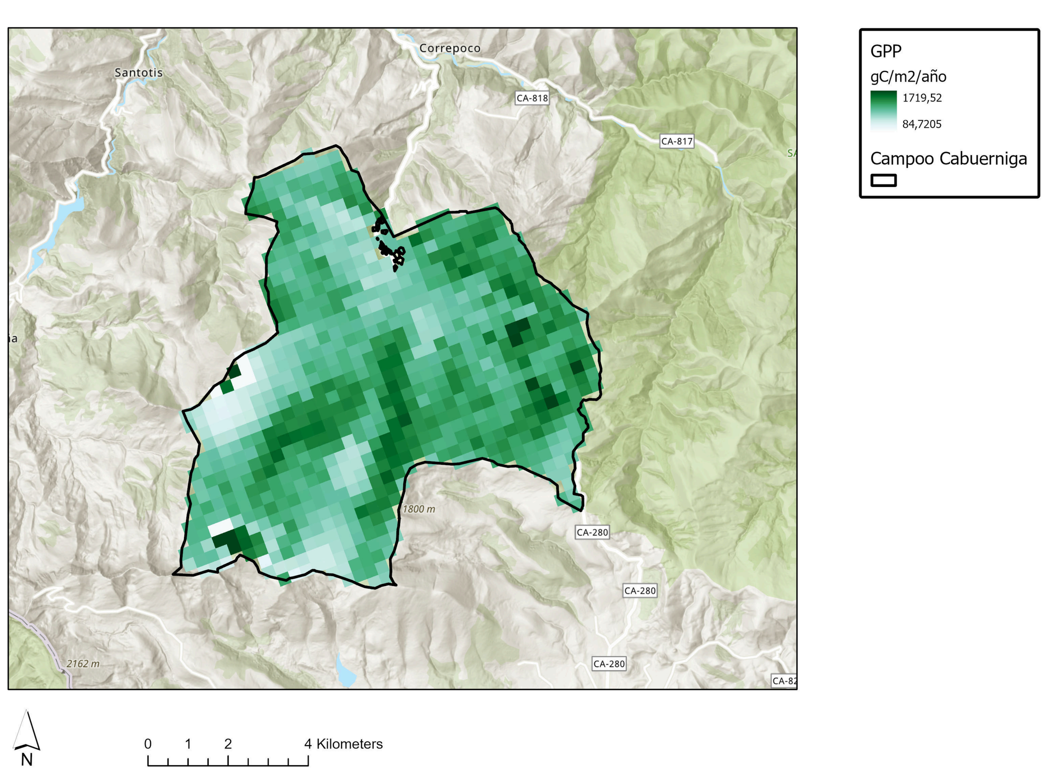
0.72 r
352 RMSE
101 bias
0.82 d

APPLICATION — Cantabria 2024

Pilot Silvopastoral Site — Northern Spain
Sentinel-3 (LST) + ERA5 (hourly meteorology) · Full year 2024

GPP ANNUAL MAP

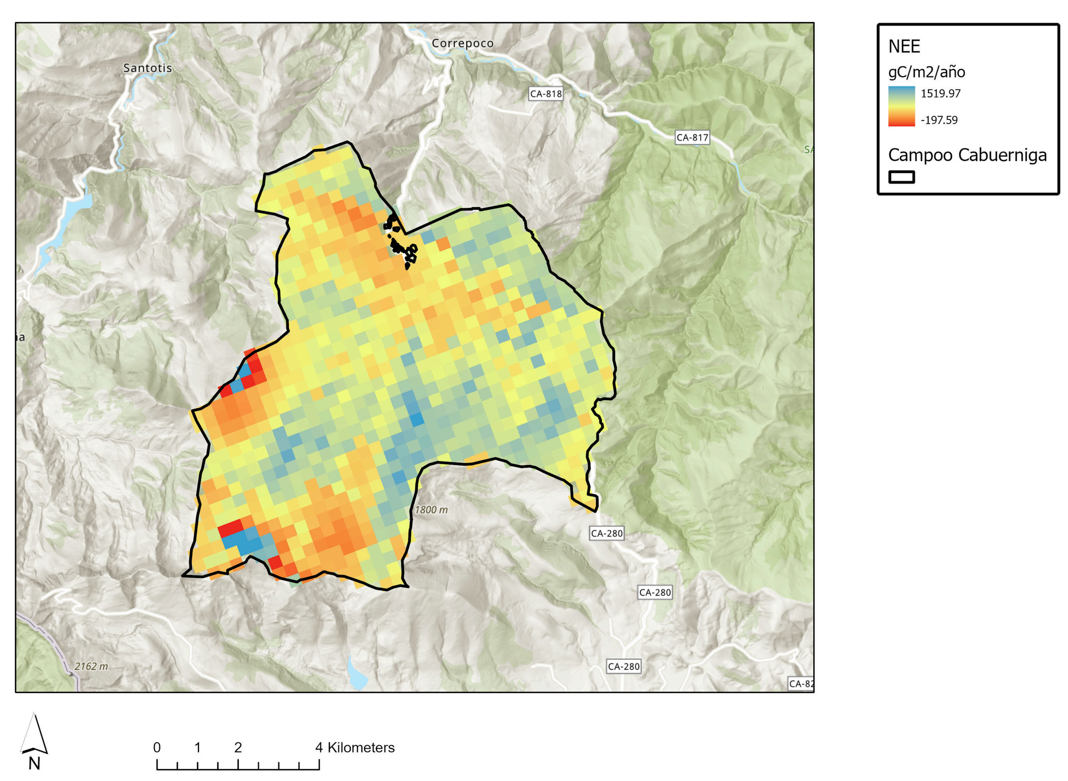
Gross Primary Production (GPP) in Campoo-Cabuerniga MUP



Gross Primary Production (gC m-2yr-1) .

NEE CLASSIFICATION

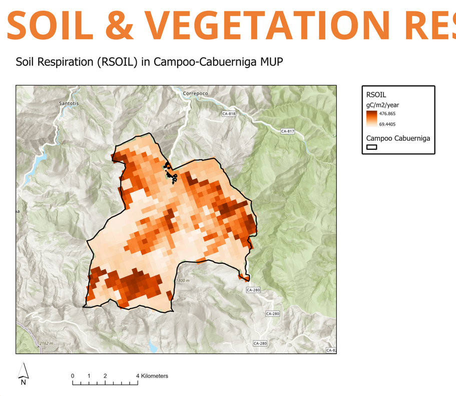
Net Ecosystem Exchange (NEE) in Campoo-Cabuerniga MUP

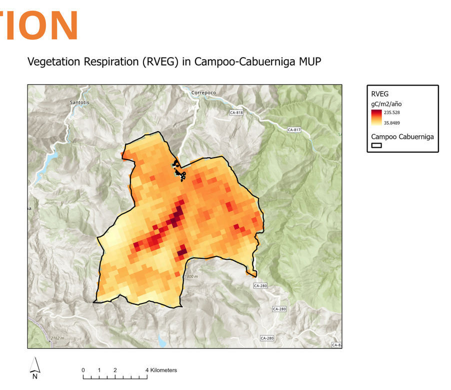


Net Ecosystem Exchange (gC m-2yr-1) .

Key finding: Vegetation density and soil moisture drive significant differences in carbon fixation between parcels — enabling parcel-level sink/source classification relevant for carbon markets and agri-environmental policy.

SOIL & VEGETATION RESPIRATION





CONCLUSIONS

Sat4Carbon: Towards Operational Agroforestry Carbon Monitoring

01 The **TSEB–Farquhar integration** enables operational estimation of GPP and NEE in silvopastoral ecosystems using Copernicus data — without site-level empirical calibration, making it fully scalable at landscape scale

02 **Validation against the ICOS Warm Winter 2020 network** demonstrates good agreement in cumulative annual GPP across multiple European biomes, confirming the transferability of the approach

03 **Water stress captured via g** is key for classifying parcels as carbon sinks or sources, with direct implications for carbon markets, policy design, and agroforestry management decisions

REFERENCES

[1] Gabourel-Landaverde et al. (2025). Identifying target areas for agroforestry in European agricultural landscapes. Agric. Syst.
[2] IPCC (2006). Guidelines for National Greenhouse Gas Inventories. IGES, Japan.
[3] Farquhar, von Caemmerer & Berry (1980). A biochemical model of photosynthetic CO_2 assimilation in C3 species. Planta, 149, 78–90.
[4] Norman, Kustas & Humes (1995). Source approach for estimating soil and vegetation energy fluxes. Agric. Forest Meteorol., 77, 263–293.
[5] Tuzet, Perrier & Leuning (2003). A coupled model of stomatal conductance, photosynthesis and transpiration. Plant Cell Environ., 26, 1097 - 1116.
[6] Kustas & Norman (1999). Evaluation of soil and vegetation heat flux predictions using a two-source model. Agric. Forest Meteorol., 94, 13–29.
[7] Leuning (1995). A critical appraisal of a combined stomatal-photosynthesis model for C3 plants. Plant Cell Environ., 18, 339–355.
[8] Monteith (1972). Solar radiation and productivity in tropical ecosystems. J. Appl. Ecol., 9, 747.