

MAPPING SOIL WATER AND CARBON FROM PLOT TO WATERSHED WITH MULTI-SOURCE DATA

CARTOGRAPHIE DE L'EAU DU SOL ET DU CARBONE DE LA PARCELLE AU BASSIN VERSANT AVEC DES DONNÉES PROVENANT DE SOURCES MULTIPLES

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ABSTRACT

Perennial Mediterranean crops such as orchards and vineyards display strong variability in water-use and inter-row management. Inter-rows may be left grassed to ease pruning and harvest, or ploughed to reduce competition for water with the trees. Irrigation can be applied via drippers, micro-sprinklers or flooding, each influencing the fate of soil organic carbon (SOC). Assessing SOC variability at regional scales, especially in relation to irrigation practices, remains challenging.

A multi-scale approach was applied in the Ouvèze-Ventoux watershed (southeastern France), where orchards and vineyards dominate. Soil samples from 17 plots (0-30 cm depth) were analyzed for SOC, physico-chemical properties and visible-mid-infrared spectra. Spectral calibration (PLSR or Cubist) yielded a high R^2 (~ 0.89), enabling the detection of intra-field SOC variations ($5-45 \text{ g kg}^{-1}$) across four orchards under contrasting management (grass vs. no-grass; drip-micro-sprinkler vs. no irrigation). An electromagnetic induction (EMI) survey performed on the same fields revealed an emerging correlation between in-phase EMI signal and SOC ($R^2 \approx 0.44$), suggesting EMI could qualitatively map SOC at field scale. Sentinel-2 imagery (using winter scenes with lowest NDVI) also correlated with field-averaged SOC ($R^2 \approx 0.60$), indicating the potential for watershed-wide SOC mapping using satellite data.

Satellite data from Sentinel-1 and 2 were also used to determine soil moisture dynamics using data over four years for five orchards, measuring surface (0-5 cm) and 0-50 cm depth water stock. A random-forest model integrating Sentinel-1 backscatter (VV, VH), Sentinel-2 derived spectral indices (FCOVER, Redness Index), Copernicus Soil Water Index, and local rainfall achieved an overall fit of $R^2 \approx 0.7$ for moisture predictions. The model performance indicates that satellite-based monitoring of field-scale soil moisture is feasible for present and past times. It should be however tested before applying it to other pedoclimatic contexts.

Combining spectrometric SOC estimates, remote-sensing moisture retrievals, and geophysical EMI measurements offers a diachronic framework to interpret SOC evolution alongside water availability and irrigation management across Mediterranean agroecosystems.

Keywords: Perennial Mediterranean crops; irrigation practices; orchards and vineyards; Copernicus Soil Water Index; soil moisture.

RESUME

Les cultures méditerranéennes pérennes telles que les vergers et les vignobles présentent une forte variabilité en matière de l'utilisation de l'eau et la gestion inter-rang. Les inter-rangs peuvent être laissés gazonnés pour faciliter l'élagage et la récolte, ou labourés pour réduire la concurrence pour l'eau avec

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les arbres. L'irrigation peut être appliquée via des goutteurs, des micro-asperseurs ou des inondations, chacun influençant le devenir du carbone organique du sol (SOC). L'évaluation de la variabilité du SOC à des échelles régionales, en particulier en ce qui concerne les pratiques d'irrigation, reste difficile.

Une approche à échelle multiple a été mise en œuvre dans le bassin versant de l'Ouvèze-Ventoux (sud-est de la France), où dominent les vergers et les vignobles. Des échantillons de sol provenant de 17 parcelles (profondeur de 0-30 cm) ont été analysés pour déterminer le carbone organique du sol (SOC), les propriétés physico-chimiques et les spectres infrarouges moyens visibles. La calibration spectrale (PLSR ou cubiste) a donné un R^2 élevé ($\sim 0,89$), permettant la détection de variations du SOC intra-champ ($5\text{--}45\text{ g kg}^{-1}$) dans quatre vergers soumis à la gestion contrastée (herbe vs. absence d'herbe; micro-sprinkler goutte-à-goutte vs. absence d'irrigation). Une étude d'interférence électromagnétique (EMI) réalisée sur les mêmes parcelles a révélé une corrélation émergente entre le signal EMI en phase et le carbone organique du sol (SOC) ($R^2 \approx 0,44$), suggérant que l'EMI pourrait permettre une cartographie qualitative du SOC à l'échelle de la parcelle. Les images de Sentinel-2 (utilisant des scènes hivernales avec le plus faible NDVI) ont également montré une corrélation avec la teneur moyenne en SOC sur le terrain ($R^2 \approx 0,60$), ce qui indique la possibilité de cartographier le SOC à l'échelle du bassin versant à l'aide de données satellitaires.

Les données satellitaires de Sentinel-1 et 2 ont également été utilisées pour déterminer la dynamique de l'humidité du sol à l'aide de données recueillies pendant quatre ans sur cinq vergers, mesurant le stock d'eau en surface (0-5 cm) et à une profondeur de 0-50 cm. Un modèle de forêt aléatoire intégrant la rétrodiffusion Sentinel-1 (VV, VH), les indices spectraux dérivés de Sentinel-2 (FCOVER, indice de rougeur), l'indice d'humidité du sol Copernicus et les précipitations locales a atteint un ajustement global de $R^2 \approx 0,7$ pour les prévisions d'humidité. La performance du modèle indique que la surveillance satellitaire de l'humidité du sol à l'échelle de la parcelle est réalisable pour le présent et le passé. Il convient cependant de la tester avant de l'appliquer à d'autres contextes pédoclimatiques.

La liaison des estimations spectrométriques du carbone organique du sol (SOC), des relevés d'humidité par télédétection et des mesures géophysiques d'interférence électromagnétique (EMI) offre un cadre diachronique pour interpréter l'évolution du SOC ainsi que la disponibilité de l'eau et la gestion de l'irrigation dans les agroécosystèmes méditerranéens.

Mots-clés : Cultures méditerranéennes pérennes; Pratiques d'irrigation; Vergers et vignobles; Indice d'humidité du sol Copernicus; Humidité du sol.

INTRODUCTION

Perennial crops such as orchards and vineyards are typical Mediterranean crops which present a high variability in water and inter-row management. The inter-rows can be grassed to facilitate the pruning, harvest or various operations in the crops, or soil can be ploughed to avoid water competition with trees or vines. The irrigation techniques can range from no irrigation to various irrigation techniques such surface irrigation, drippers or micro-sprinklers (Rouault et al., 2025). Such variability water and inter-row management can impact the fate organic carbon in soil. There is a real challenge in assessing soil organic carbon (SOC) variability both at the field scale and between fields at the regional scale, in relation with practices and the heterogeneity they induce, in particular with the irrigation management. Along with spatial variations, temporal variation for soil water, and most importantly for soil carbon on long term, is at core of the estimation of stock variations. To that aim, long-term remote sensing data series can help us to get estimations back into the past. We propose here to combine proxy- and remotely sensed data using geophysical and spectrometric approaches to get information on soil moisture and carbon in these perennial agrosystems from the field to regional scale.

MATERIAL AND METHODS

We investigated a small watershed in southeastern France (Ouvèze-Ventoux), where orchards and vineyards predominate with a diversity of agricultural practices. Soil samples (0-30cm) were collected over a two-year period in 2024 and 2025 on 17 plots covering a large variability in irrigation practices and inter-row management. For each field, 12-15 soil samples were acquired, both in tree rows and in inter-rows and pooled separately for row and inter-row. Physical, chemical (SOC) and spectral analyses were made on air-dried, 2 mm sieved, pooled samples. Spectral measurements of soils were taken using a lab spectrometer (Spectral Evolution SM 3500) in the range of visible near-infrared to mid-infrared (350-2500 nm). Additionally, intra-field variability of SOC was investigated in 4 orchards submitted to different management practices (grass no grass, drip-micro sprinkler irrigation/no irrigation), with ~15 samples over the field, using spectral measurements. On the same 4 orchards, an electromagnetic induction (EMI) geophysical survey (Duaem 21s) was done during soil sampling to analyze relationships between SOC and EMI signal, with the aim of spatializing SOC at the field scale from EMI measurements.

To evaluate the feasibility of mapping field-averaged SOC within the studied watershed, we analyzed the correlation (using partial least square regression -PLSR or cubist models) between field-measured SOC and Sentinel-2 spectral data, focusing on the lowest NDVI values recorded during winter for both study years.

To map soil moisture (surface and water stock for 0-50 cm depth) over the Ouveze watershed, both sentinel 1 and 2 data are used using machine learning approach. Soil moisture measurements over 4 to 5 orchards for 4 years were used to train a random forest (RF) model. Input data of RF model included Sentinel 1 backscattering data (VV, VH), vegetation indices (fraction of green vegetation cover: FCOVER, Redness Index: RI) derived from Sentinel 2, Soil Water Index (at 1km resolution from Copernicus free products), daily Rainfall from a nearby weather station.

RESULTS

1. SOC evaluation with spectrometric measurements and geophysical EMI survey

The 32 samples from the 17 fields examined showed a strong correlation ($R^2=0.89$) between measured SOC and SOC predicted with spectral measurement using PLSR or cubist models (with cubist performing the best - figure 1). Most SOC values range between 5 and 25 g/kg. The highest value of SOC (49 g/kg) measured is due to the application of a high quantity organic amendments over this orchard. With this SOC-spectral data calibration, the intra-field variability over 4 contrasted orchards was examined and SOC shows coefficient of variation varying from 21 to 62%. The highest variability was found in soil showing the lowest SOC level (7 g/kg), without grass and drip irrigated. The lowest variation (21%) was associated with grassed inter-row and mini-sprinkler irrigation (SOC=22 g/kg). Non irrigated orchard and grassed inter-row with drip irrigation showed intermediate variations (28 and 30%; SOC=17 and 23 g/kg). Differences between row and inter-row for SOC was mostly driven by presence of grass in inter-row. The difference inter-row vs row range from 10 to 50% of SOC in grassed inter-row compared to row while differences are lower than 7% when inter-row is non-grassed. Drip irrigation increased SOC in the row in in some cases but still lower than 7% (Charrière et al., 2026).

The EMI geophysical survey over the 4 study fields was used to test if EMI signal could be used as a proxy estimating SOC variability at field scale. The EMI device provided out of phase soil conductivity as well as in-phase signal for 4 integrated depths from 0-50cm to 0-3m. The EMI in-phase signal showed a significant negative correlation with SOC when signal is integrated over 1.6 or 3 m depth for all the samples from the 4 fields (figure 2). Such a correlation between EMI in-phase signal and organic matter was also observed by McLachlan et al. (2022) in vineyards and suggested that it could be related to adsorption of metals on organic matter. Such relationship in our study zone suggests that EMI be could be used in that case to quickly give a qualitative mapping of SOC over the fields.

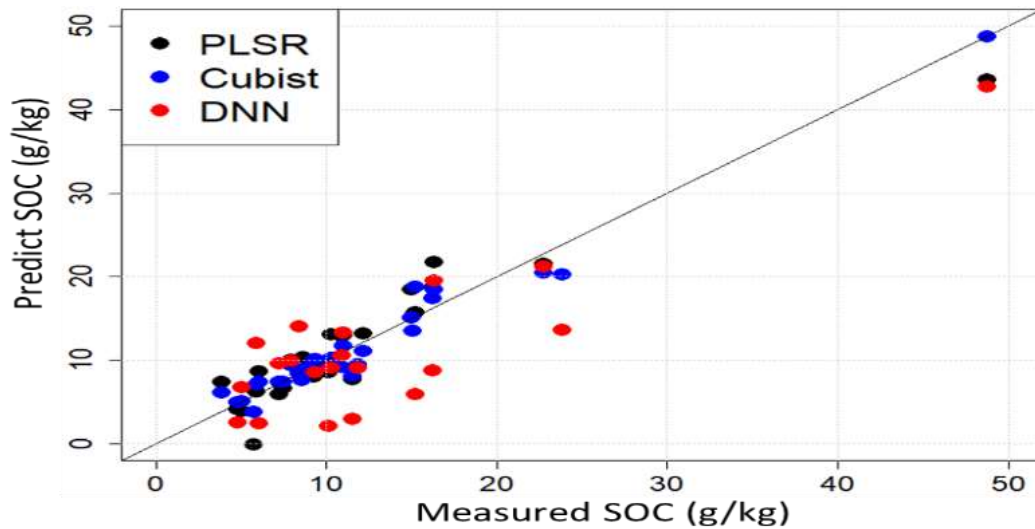


Figure 1. Calibration of SOC with spectrometer measurements for 17 field over Ouveze watershed with PLSR, cubist and DNN models.

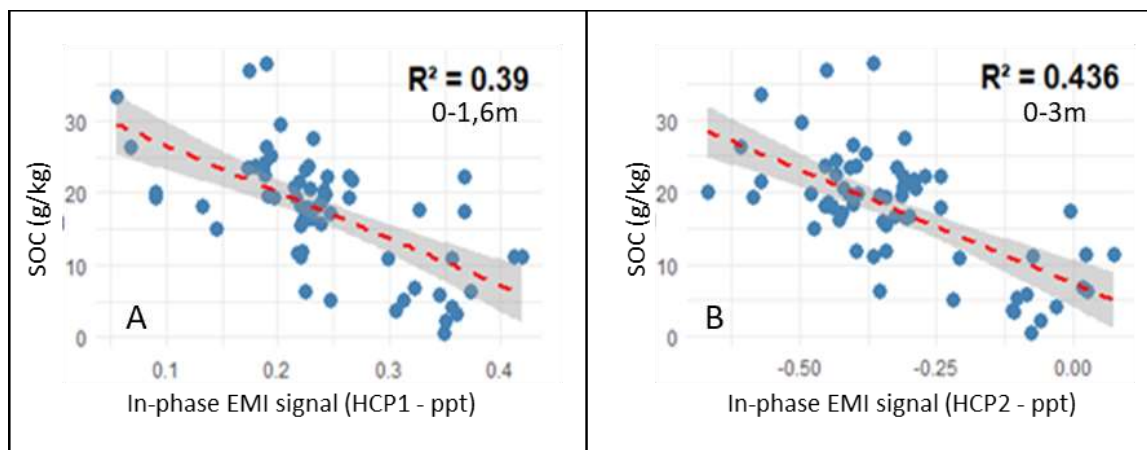


Figure 2. Correlation between SOC estimated from spectral measurements (0-30 depth samples from 4 fields) and in-phase EMI signal over 0-1.6m (A) and 0-3 m depth (B).

2. Field SOC estimation at watershed scale from remote sensing

Mean field SOC measured over the different fields was linked to spectral data of Sentinel 1 (two polarisations: VV, VH) and 2 (10 spectral bands) images, choosing images with lowest NDVI in winter. Application of PLSR with these data for predicting measured SOC resulted in good performance: $R^2 \sim 0.86$ RMSE = 2.62g/kg. With this calibration applied to Ouveze watershed, the predicted map of SOC is shown figure 3A with corresponding SOC distribution in 3B. The SOC values varied from 2.2 to 47.3 g/kg, with the median at 14 g/kg. This value was slightly higher than the mean values of our soil database measured in lab. This can be explained by the fact that the majority of orchards were grassed which led to slightly higher values than tilled plots (Rouault et al., 2024).

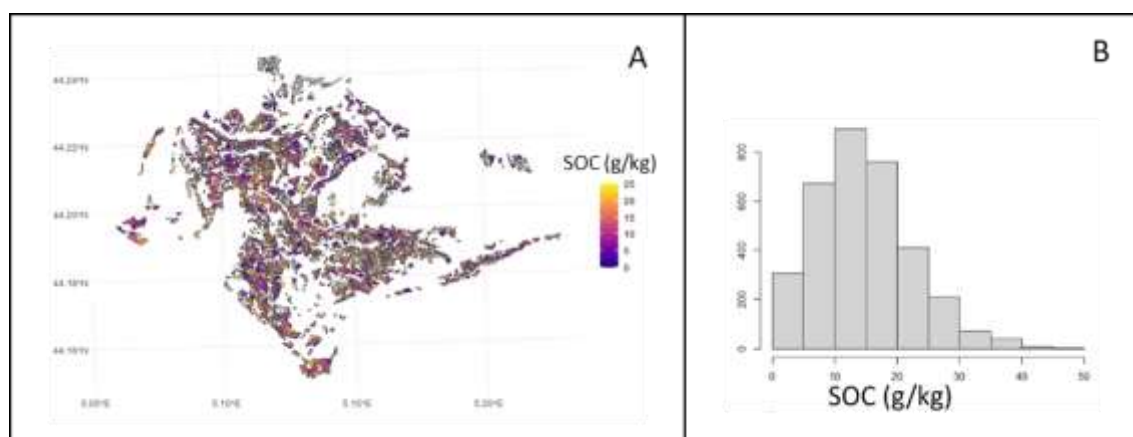


Figure 3. A/ SOC map at the Ouvèze-ventoux watershed estimated with prediction of the PLSR model using sentinel data and B/ the corresponding SOC distribution

3. Soil water evaluation from S1 and S2 data

Vegetation/soil indices FCOVER, Redness index (RI) were calculated from S2 images at 10 m resolution and averaged over the fields monitored for water content, S1 backscattering data (VV, VH) and incidence angle were also averaged over the fields. Easily accessible additional data from Soil Water Index from Copernicus³ (1 km resolution) and available rainfall data were also added. These different variables were shown to impact the most training and prediction of soil water with random forest (RF) modelling (Kalenga Tshingomba et al., 2024). The modeling strategy was to train the RF with 50% randomly chosen of available ground data for study orchards (2021-2024), separately for spring/summer and autumn/winter periods. The performances of RF model for validation data are summarized table 1, showing a good agreement between predicted and actual values ($R^2 \sim 0.7$) for both surface soil water content soil water stock 0-50 cm. Importantly, the RMSE of soil water stock (0-50 cm) is ~ 9 mm for mean stocks of 90 mm.

Table 1. Performance of Random Forest model with correlation coefficient (R^2) and Root mean square error (RMSE) for estimating surface soil water content and soil water stock 0-50cm.

	R2	RMSE
Soil water content@5cm	0.74	0.03 cm ³ /cm ³
Soil water stock 0-50 cm	0.67	8.8 mm

Figure 4 shows the fit of the model for soil water stock for 3 irrigation settings in orchards. The RF model can track water stock time variation in orchards but under estimation happens in dry season, greater for drip than micro-sprinkler irrigation and with the lesser bias when no irrigation is applied. This underestimation comes in part from S1 and S2 resolution and (10m) and more or less localized irrigation and averaging of water content at the field level.

It should be noticed that these results were obtained within a in the watershed exhibiting a rather homogeneous soil texture and the model should be tested and possibly retrained before applying it to other pedoclimatic contexts.

³ <https://www.copernicus.eu/en/access-data/copernicus-services-catalogue/soil-water-index-2015-present-raster-1-km-europe-daily>

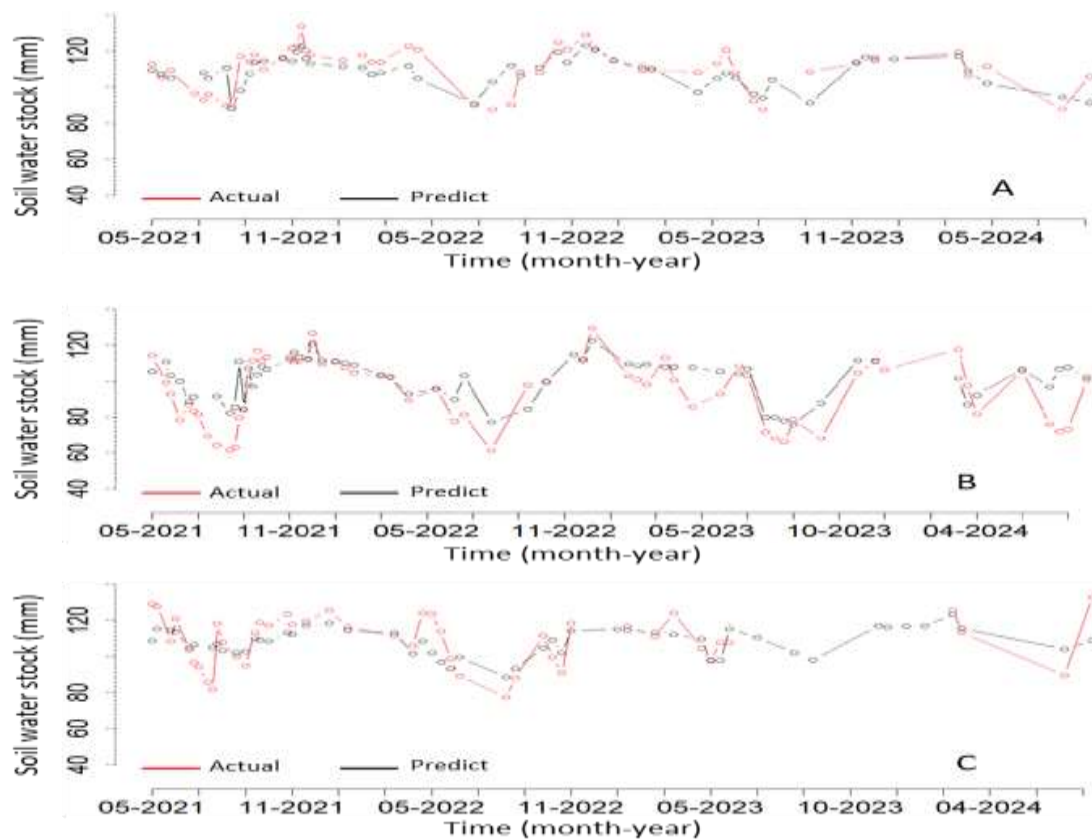


Figure 4. Actual and predict soil water stocks (0-50cm depth) in 3 orchards with different irrigation management: A/ No irrigation, B/ drip irrigation, C/ micro-sprinkler irrigation. Prediction is made with a trained random forest model using Sentinel-1 and 2 data

CONCLUSION

We show here that with remote sensed data such as from Sentinel-1 and 2 at high spatial and temporal resolution, soil water and carbon averaged at the field level could be predicted for orchards and further used to map both variables at the landscape level. This opens a way to study interactions between carbon and water at this scale, and possibly to try to estimate these variables back in the past for long term estimations (from 2016 with S1 and 2). At the field scale, calibration of carbon content with spectra measurements on soils from various fields enable to estimate more easily the intra-field variability of SOC. A possible link between C and in-phase EMI signal, as found in our study place, may be a step forward to map qualitatively C in the fields.

Acknowledgments

The authors acknowledge funding from the PEPR FAIRCARBON project SLAMB. They also acknowledge support from the CSIRO–INRAE Joint Linkage Program and the INRAE Agroecosystem Department for France–Australia visits and collaborative meetings.

REFERENCES

- Charrière S., Pelosi C., Bérard A., Doussan C., Flamain F., Chapelet A., Courault D. 2026, How intra- and inter-field management drives soil biology and soil organic carbon in perennial Mediterranean crops? In prep.
- McLachlan P., Schmutz M., Cavailhes J., Hubbard S.S. 2022, Estimating grapevine-relevant physicochemical soil zones using apparent electrical conductivity and in-phase data from EMI methods. *Geoderma*, 426, 116033.

- Rouault P, Courault D, Pouget G, Flamain F, Diop P-K, Desfonds V, Doussan C, Chanzy A, Debolini M, McCabe M, et al. 2024, Phenological and Biophysical Mediterranean Orchard Assessment Using Ground-Based Methods and Sentinel 2 Data. *Remote Sensing*, 16(18):3393.
- Rouault P., Courault D., Flamain F., Pouget G., Doussan C., El Hajj M.M., Al-Mashharawi S. K., McCabe M., and Debolini M. 2025. Integration of Sentinel-2 Data into the Simetaw Model for Assessing Irrigation Water Requirements and Evapotranspiration. *Agricultural Water Management*. 317: 109637
- Kalenga Tshingomba U., Courault D., Baghdad N., Flamain F., Chapelet A., Pouget G., Doussan C. 2024, Monitoring of Irrigated Mediterranean Crops in Southeastern France from Sentinel 1 & 2 Data. *IGARSS 2024 - 2024 IEEE International Geoscience and Remote Sensing Symposium*, Jul 2024, Athènes, Greece. pp.4932-4935