Potential of proximal hyperspectral imaging to estimate the spatial and temporal variability of soil microbial respiration.

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[Introduction]

The spatial heterogeneity of soil properties, especially the distribution of organic matter and biological activities, has often been emphasized to understand soil behavior, for example its resistance to stress. It is difficult to understand, quantify and follow the evolution of soil respiration over space and time. Although NIR spectroscopy is not relevant to directly measure carbon dioxide (CO_2) emissions, soil respiration involves organic matter degradation thus biochemical changes, which could be estimated with Near Infrared Spectroscopy (NIRS).

The objective of this study was to evaluate the potential of proximal hyperspectral imaging in the Visible-Near Infrared (VIS-NIR) to (i) calibrate a model to predict soil respiration under controlled conditions, and (ii) to determine both spatial and temporal variations in soil respiration at a 0.2-mm scale.

[Materials and methods]

- Calibration database:

The soil studied was a calcic Fersialsol, clayey, from southern France. Two batches (A and B) of 28 soil samples (10g) mixed with variable amounts of straw (0% to 100%) were incubated under controlled temperature and moisture conditions during 28 days. Two soil water potential (-0.01 MPa and -0.1 MPa) were tested. Soil samples were stressed at 60°C (stressed samples) or at 28°C (control samples) for 24h before beginning the incubation assays. Soil respiration (in mgC-CO_2 g^{-1} soil) was determined at different dates (D0, D1, D3, D7, D14, D21 and D28) using sodium hydroxide traps. At each date, hyperspectral images of these samples were acquired with a HySpex VNIR-1600 camera from Norsk Elektro Optikk (spectral range 415-993 nm) at a distance of 1 m. The mean spectrum of each sample was extracted from the images in order to build a calibration database associating a spectrum (Sp_t) to accumulated respiration ($DSR_{0\text{-}t}$) over the period considered (Figure 1).

- Calibration model:

Four different models using the Partial Least Square algorithm were built based on the calibration database (n=336). In the first approach, mean sample spectra (Sp_t) at a given date (t) were fitted to accumulated respiration of the sample since D0 ($DSR_{0\text{-}t}$). In the second approach, we fit the difference ($\Delta Sp_{0\text{-}t}$) between the spectra SP_0 measured at D0 and the spectra Sp_t measured at Dt with the same accumulated respiration value DSR_{0-t}. For both strategies, either the whole wavelength range (415 – 993 nm) or only the NIR range (700 – 993 nm) was used.

- Predicted soil respiration maps:

The first two models were applied to each pixel (0.04 mm^2) of the hyperspectral images acquired at the same dates on four soil mesocosms (400 cm^2) incubated in similar conditions than the standard sample. The four mesocosms differed by the amount of straw that had been added to soil (0% and 0,04%) and by the application or not of a thermal stress before incubation (24 h at 60°C).

The *predicted soil respiration maps* of the mesocosms were then visually compared in order to identify possible spatial patterns or hotspots, and their evolution with time.

[Results and discussion]

- Quality of the calibration models :

It was possible to use the spectral information from hyperspectral images to predict the amount of CO_2 released by the soil during incubation (Table 1). The quality of the model decreased when the sole NIR part of the spectrum was used (Models 2 and 4), but it was a way to avoid building a prediction model based on the color.

The best calibration strategy (Model 3 > Model1) was to use the difference spectrum (ΔSp_{0-t}) between two dates to predict respiration. The difference spectrum could sign the loss or the transformation of some soil organic matter by microbial activity.

In order to validate the relevance of the *soil respiration maps* obtained, Model 1 was applied on an image of the standard sample (Batch A) at D28. A value of predicted soil respiration per sample could be extracted from this map by averaging all the pixels of the same sample. The comparison between the measured respiration and the average predicted value from the soil respiration map lead to a correlation coefficient of $R^2 = 0.879$ (Figure 2).

- Spatial and temporal variability of soil respiration:

Only Model 1 and 2 could be applied on mesocosm hyperspectral images because it was hardly possible to exactly fit images at two consecutive dates to calculate the difference spectra (ΔSp_{0-t}) at each exact pixel.

Although the predicted soil respiration maps obtained by applying models using the whole spectral range (415 – 993 nm) on mesocosm hyperspectral images appeared very noisy, some distinctive respiration patterns linked to coarse organic particles or fine roots could be recognized (Figure 3 Comparison of the soil respiration prediction maps (using Model 1) at D1 and D21 in a detailed area containing a root). Comparison between predicted soil respiration maps at different dates (D1 and D21) revealed that the respiration intensity of organic residues decreased with time.

[Conclusion]

This study shows that it is possible to use hyperspectral images to build a soil respiration model. It is also meaningful to apply a model on another image in order to obtain a soil respiration prediction maps.

The interpretation of the prediction map still faces some technical problems such as the fitting of two consecutive images of the same mesocosm.

[Novelty]

Proximal hyperspectral imaging of soils to perform soil respiration calibration;

Application of a prediction model on an hyperspectral image.

[Summary]

The objective of this study was to evaluate the potential of proximal hyperspectral imaging to (i) calibrate a model to predict soil respiration under controlled conditions, and (ii) to determine both spatial and temporal variations in soil respiration at a hundreds of micrometer scale. Calibration models based on spectra and respiration measured on standards were built then applied on hyperspectral images acquired on soil mesocosms (400 cm^2), in order to predict their respiration pixel by pixel (0.2 mm^2). The quality of the models was acceptable but their application to produce prediction maps faced some technical problems due to hyperspectral technology.

[Keywords]

Soil respiration, proximal hyperspectral imaging, PLS, spatial variability

Hyperspectral image acquisition date	D0	D1	D3	D7	D14	D21	D28
Sample mean spectra	Sp_0	Sp_1	Sp_3	Sp_7	Sp_{14}	Sp_{21}	Sp_{28}
Difference spectra ΔSp			$\Delta Sp_{0-14} = SP_0 - SP_{14}$				
Measured CO_2 emission (soil respiration (SR) in mg $C\text{-}CO_2\ g^{-1}$ soil)	0	SR_1	SR_3	SR_7	SR_{14}	SR_{21}	SR_{28}
Accumulated CO_2 emission ΔSR (soil respiration in mg $C\text{-}CO_2\ g^{-1}$ soil)			$\Delta SR_{0-14} = SR_1 + SR_3 + SR_7 + SR_{14}$				

Figure 1 Data acquisition protocol

Table 1 Soil respiration calibration models

Model	X Y	n samples	R^2	Biais	Standard error of cross validation (mg $C\text{-}CO_2.g^{-1}$ soil)
Model 1	X : Sp_t (VIS-NIR) Y: $\Delta SR_{0\text{-}t}$	336	0.73	0.348	547
Model 2	X : Sp_t (NIR) Y: $\Delta SR_{0\text{-}t}$	336	0.575	6.98	693
Model 3	X : $\Delta Sp_{0\text{-}t}$ (VIS-NIR) Y: $\Delta SR_{0\text{-}t}$	280	0.826	-1.21	427
Model 4	X : $\Delta Sp_{0\text{-}t}$ (NIR) Y: $\Delta SR_{0\text{-}t}$	280	0.704	4.55	558

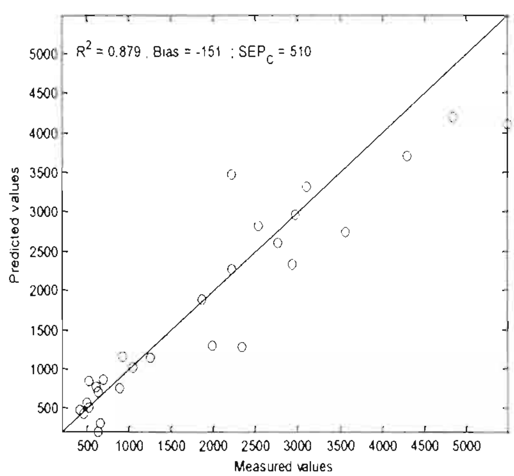

Figure 2 Laboratory measured values of soil respiration of 28 standard samples (Batch A) vs. average values extracted from the soil respiration maps obtained by applying Model 1 of the same samples at the same date (D28)

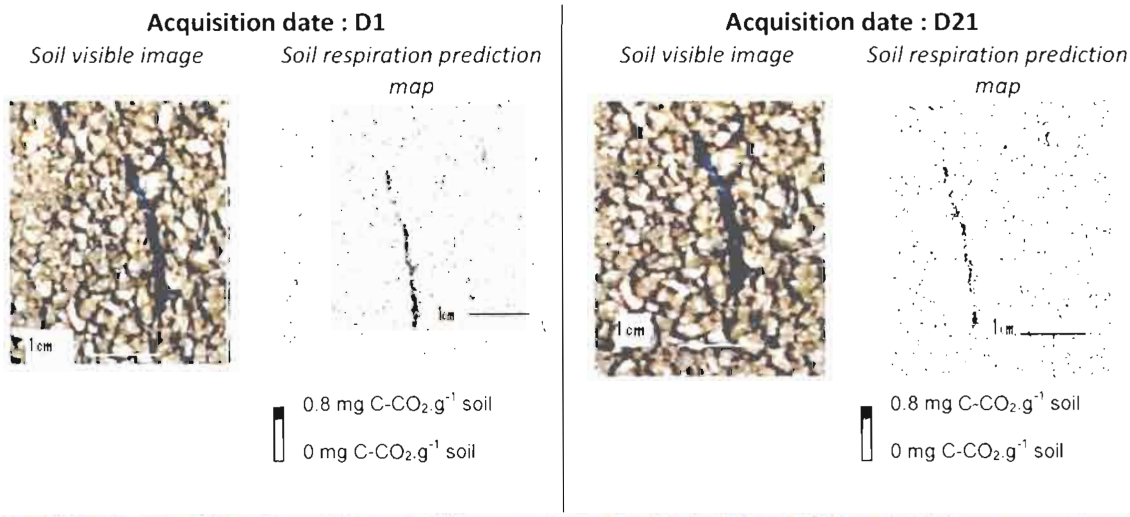

Figure 3 Comparison of the soil respiration prediction maps (using Model 1) at D1 and D21 in a detailed area containing a root