Using process models, remote sensing and spectrometry to open scientific locks in agroforestry systems: *the example of coffee in Costa Rica*

International Symposium on Agroecology for Food and Nutrition Security, FAO, Rome, 18-19 sept. 2014

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Introduction

- Agroecological systems are more complex than conventional ones, due to multiple-cropping and cycles, and to subtle interactions in time and space. They require specific tools to cope with this peculiar complexity. Agroforestry for instance is a crucial agroecological option to address sustainability, biodiversity, productivity in low-supply conditions and market diversification. However, subtle trade-offs or synergies exist between enhanced resource capture provided by the shade trees and competition / facilitation between shade trees and the main crop.
- We argue that the recent development of tools, such as refined process models (suitable to address the intra-plot variability of energy and mass fluxes) combined with remote sensing and spectrometry are very promising to optimize the shade tree design in plots, according to e.g. microclimate, elevation, exposure or nutrient supply level experienced by the crop. Virtual simulation combined with field verification should ease the process of adapting management practices to global changes.
- The present poster aims at showing how some scientific locks can be opened by novel methods, which used in combination can help optimizing the agroecological performances in Agroforestry systems.

Photo 1: Coffee agroforestry farm on volcanic soils in Aquiares, Turrialba, Costa Rica, with large (20 m high) shade trees

Development

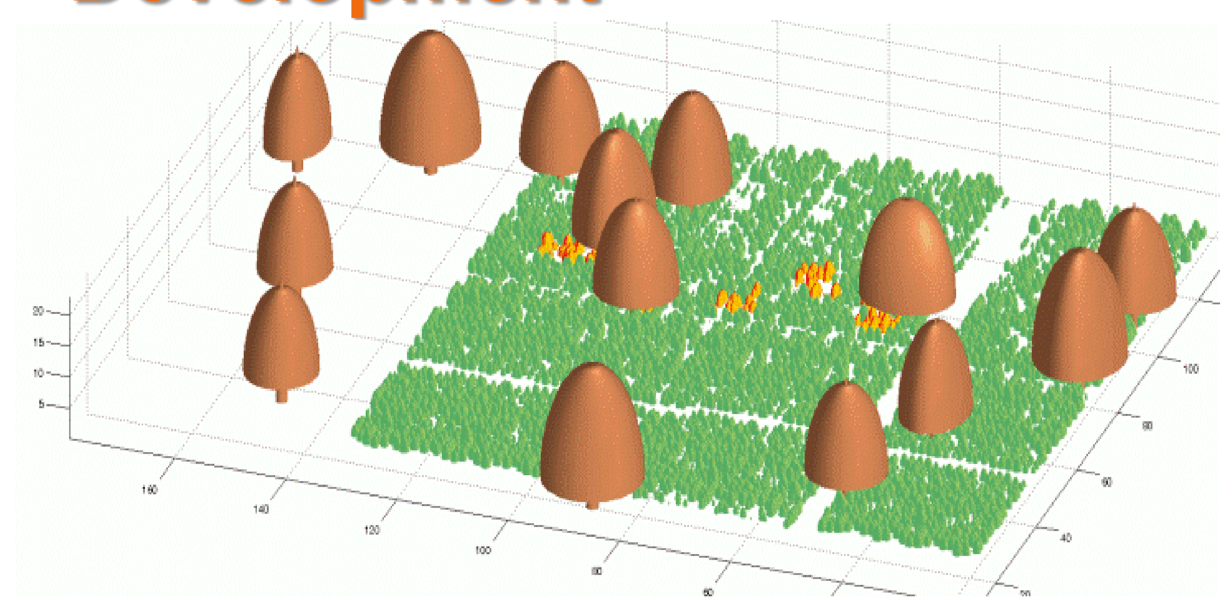

Fig. 1: Sketch map of a virtual plot with shade trees (brown semi-ellipsoids, upper-layer) and coffee plants (green, understory), as simulated with the MAESPA model (Duursma and Medlyn, 2012) after extensive field survey for architectural parameterization. Source: Charbonnier et al. (2013).

Question 1: How does shade affect the understory crop?

- **Lock:** so far, heterogeneous plots such as agroforestry have been represented mainly using with 2 simplified and discontinuous situations, "below the shade tree" or in "full sun". However, the light budget of the understory plants is actually a continuous variable, depending on the leaf area of each plant in the field, of its neighbors, of the exposure, slope and time of day and finally of the distance to the shade trees.
- **Innovation:** a 3-D model (Duursma and Medlyn, 2012) was used to map light absorbed by the coffee-layer, with the horizontal resolution of the coffee plant (**Fig. 1**). It yielded a continuous representation of light gradients inside the plots (**Fig. 2a**), the variability of which is clearly detectable on virtual transects (**Fig. 2b**) (Charbonnier et al., 2013).
- **Outputs:** Such a continuous representation of the available light for any given plant inside a mixed heterogeneous plot (whatever plant architecture, leaf area, layers, neighbors etc.) allows to 1/ study competition for light in complex plots 2/ represent canopy temperature maps, carbon and water fluxes per plant layer and per plot, 3/ compute light budgets per plant from the hour to several years, 4/ design new experiments inside the plots (for instance for studying yield or impact of diseases) using the light absorbed as a new useful continuous co-variable 5/ adapt the shade tree density to the local conditions (elevation, exposure and temperature requirements of the crop in a changing climate, Roupsard et al., 2014).

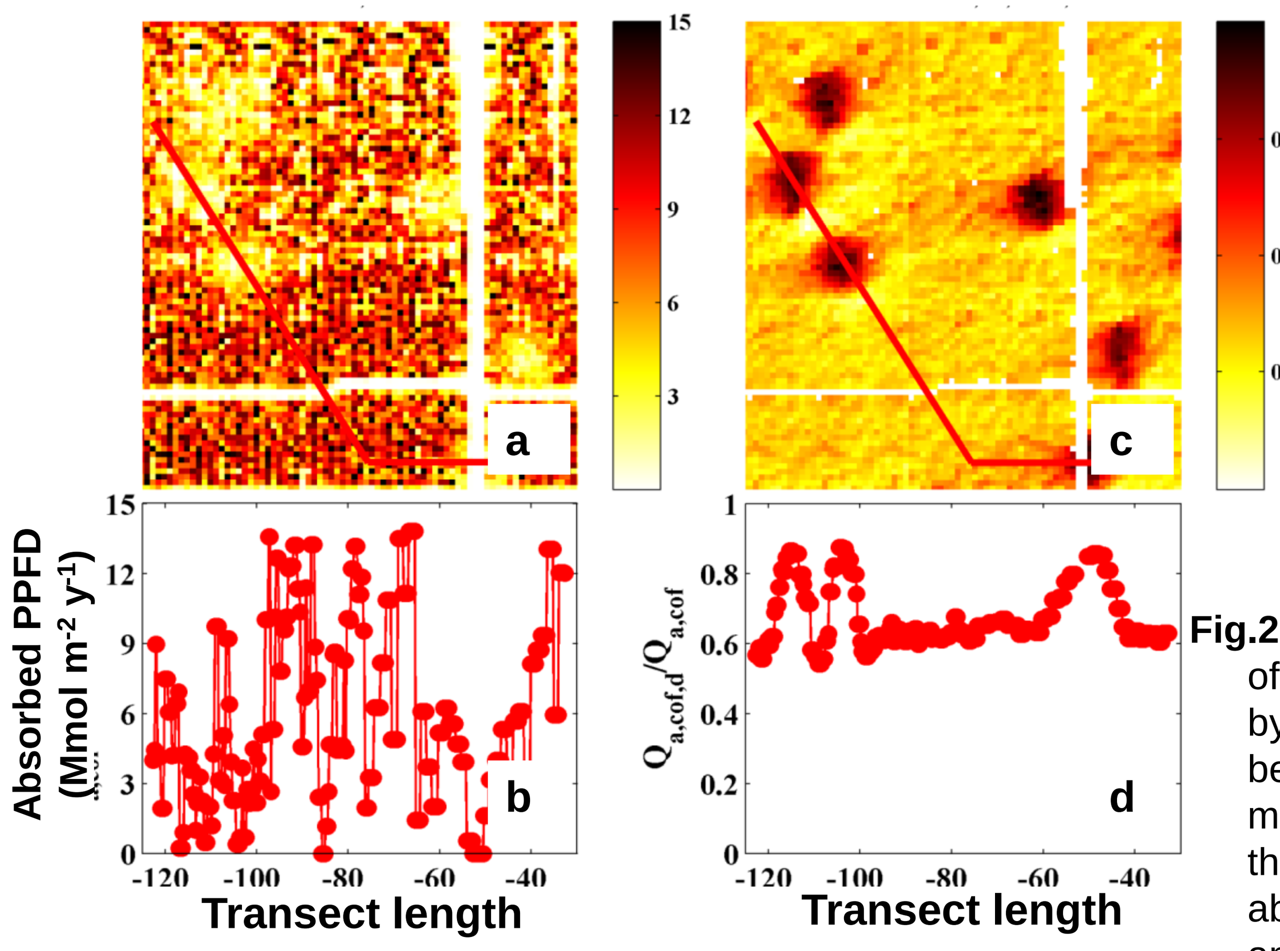

Fig.2: Same sketch map as in Fig. 1, now vertical view. **a/:** map of the amount of light (PPFD = Photosynthetically active Photon Flux Density) absorbed by the coffee layer, when cumulated over one year (yellow spots rather below shade trees and red colors in full sun), simulated with the MAESPA model (Duursma and Medlyn, 2012); **b/:** variability of the absorbed light by the coffee layer along the red transect from a; **c/:** fraction of diffuse light absorbed by coffee plants below shade trees (red spots, more diffuse light) and in full sun; **d/:** transect. Source: Charbonnier et al. (2013).

Question 2: is there any link between vegetative development of the plant (coffee) and its fruit yield?

- **Lock:** yield prediction at the regional scale is crucial to adjust the whole chain of harvest and post-harvest to the annual fluctuations of production and to minimize wastes. It was suspected that the development of vegetative parts in plants is correlated, positively or negatively, with the fruit yield. How does vegetation index mapping help predicting yield then?
- **Innovation:** the vegetation index can be mapped at the regional scale using remote sensing (**Fig. 3**) (Taugourdeau et al., 2014), while the fruit yield is much more difficult to sense.
- **Outputs:** although coffee fruit yield is predicted at around 50% by amount the fertilizer input, adding the remotely sensed leaf area index in the model allowed improving the prediction to 79%, considering the scale of a large farm (data not shown).

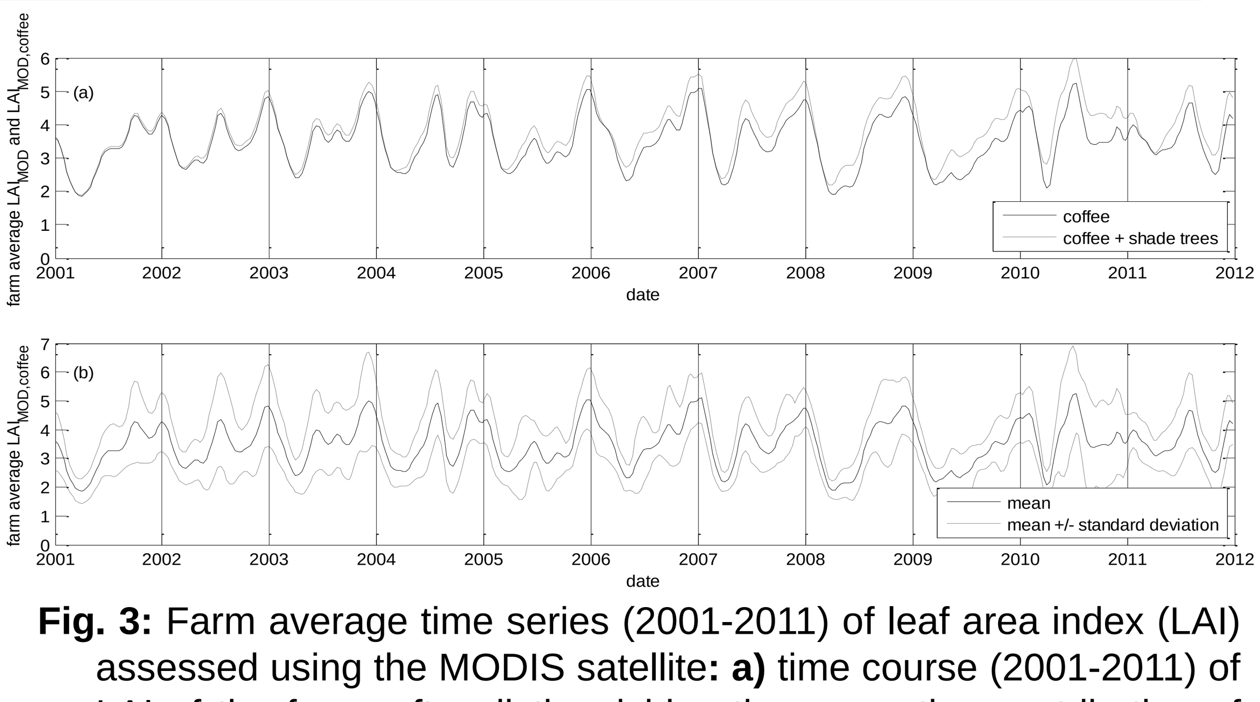

Fig. 3: Farm average time series (2001-2011) of leaf area index (LAI) assessed using the MODIS satellite**: a)** time course (2001-2011) of LAI of the farm, after distinguishing the respective contribution of coffee and shade trees; **b)** time course of coffee LAI, averaged over the entire Aquiares farm and its standard deviation (107 MODIS pixels). Source: Taugourdeau et al. 2014.

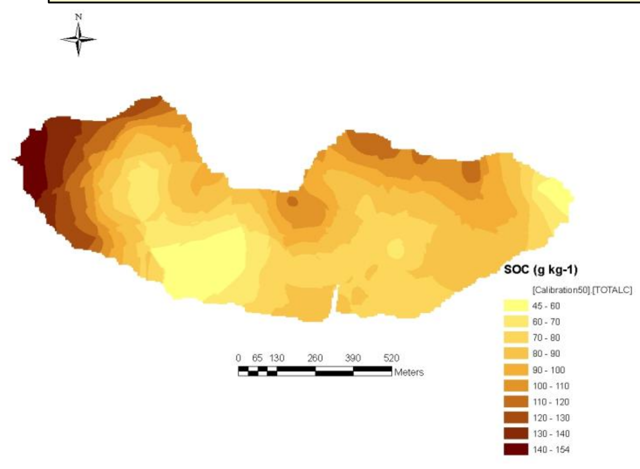

Fig. 4: Map of superficial soil organic carbon (SOC: g kg[-1]) obtained after sampling 500 points in 1 km2 watershed planted with coffee agroforestry system, using VIS-NIR spectrometry with calibration procedure and finally kriging. Source: Kinoshita (2012). SOC shows very high levels and large variability (50-150 g kg-1) in this volcanic Andosol.

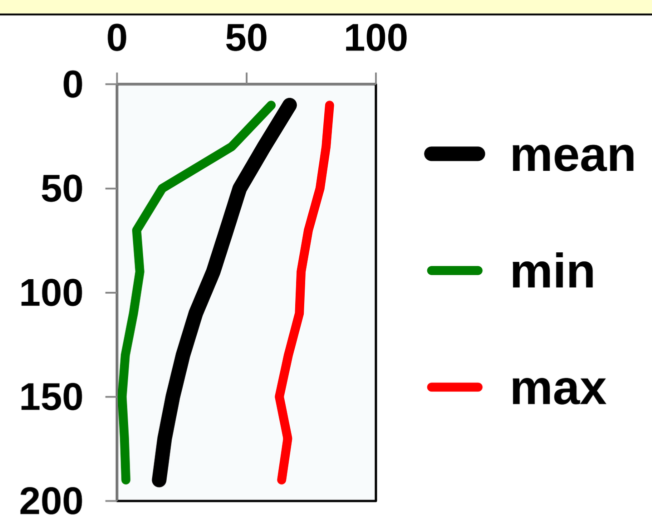

Fig. 5: Vertical profiles, and their variability throughout the 1 km^2 watershed presented in **Fig. 4**. Note high values of SOC in surface, and very deep accumulation along profiles (>2 m) leading to huge carbon stocks permitted by the soil composition (Andosol, metal-humus complexes and allophane). Source: (Albrecht A. et al., unpubl.)

Question 3: What is explaining the variability of soil carbon stock, the land cover or the soil parameters?

- **Lock:** stocks of C in soils are very difficult to assess, due to 1/strong horizontal variability in superficial soil organic content (SOC), 2/deep carbon profiles, 3/dry bulk density variability issues, 4/high cost of SOC analysis
- **Innovation:** using fast-screening methods for SOC assessment, such as Visible + Near Infrared (VIS-NIR) and Mid Infrared (MIR) spectrometry, allows mapping SOC horizontally at the landscape scale with high number (500) of points (**Fig. 4**) (Kinoshita, 2012), and also according to soil depth (**Fig. 5**).
- **Outputs:** such studies reveal that in this peculiar type of volcanic soil, the horizontal and vertical heterogeneity of SOC is much more relying on the heterogeneity of the soil material (clay, metal-humus complexes and allophane content) than on land cover (distance to shade trees or leaf area index) or topography (slope, distance to river-beds etc.). This conclusion is not universal, and can change according to soil types and cover dynamics, but such rapid techniques help C stock assessment a lot.

Conclusions

The recent development of tools, such as process models with resolution from plant to plot, remote sensing and fast-screening C analysis in soils, when used in combination allow refined understanding of processes (competition, facilitation, compensation) and occurring in complex and multi-layer agro-ecological systems, such as agroforestry, and drive optimization efforts.

Acknowledgements: EU-CAFNET Project; ANR-ECOSFIX SYSTERRA project; ANR/AIRD-MACACC AGROBIOSPHERE project (ANR-13-AGRO-0005); CIRAD/Eco&Sols-Coffee-Flux collaborative platform http://www5.montpellier.inra.fr/ecosols/Recherche/Les-projets/CoffeeFlux; CIRAD ATP-SAFSE Project (http://safse.cirad.fr/). The Barquero Family. The Aquiares Farm.

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