Challenges in establishing digital maps of soil organic carbon in Madagascar

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- **Soil in Madagascar**

Madagascar is an island located in Eastern Africa (Fig.1) in the Indian Ocean (area of 587,000 km², between 11°57 and 25°29 S and 43°14 and 50°27 E) with a tropical climate characterized by a variety of vegetative cover: Forest, shrub fallow, agricultural land, bare land, mangroves… (Fig.2 respectively (a) to (e)). The geomorphology roughly consists of three parallel longitudinal zones: central highland, humid coastal strip in the east, and zone of low highland and plains in the west. Dominant soil types are Ferralsols (Ferralitic soil) and Ferric Luvisols (Ferruginous soil) covering over 46% and 28 % of national area respectively (Fig.1).

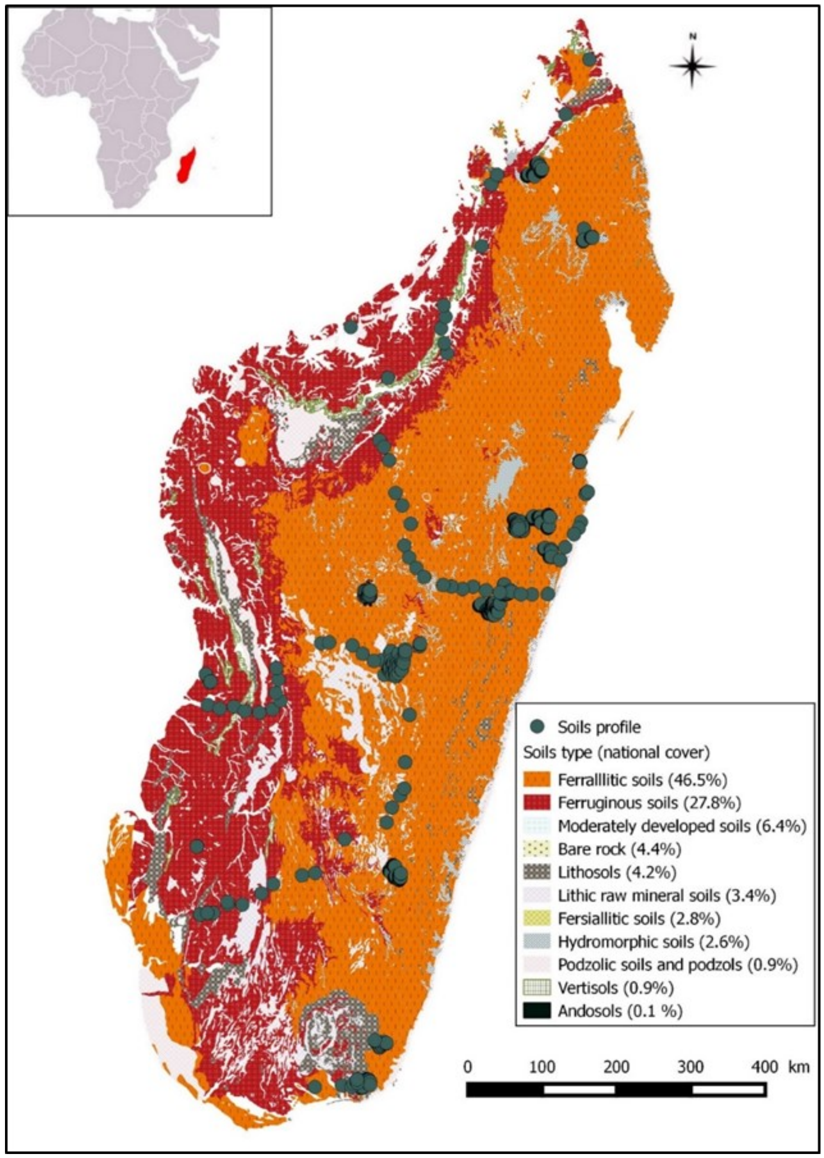

Fig. 1. Soil distribution in Madagascar (Delenne and Pelletier, 1981) with location of soil profiles studies on 2010 to 2015 (n = 1,993)

It is an island where its natural resources present a richness not only in the biodiversity of flora and fauna but also in terms of soil. This soil resource has an important place given that more than 80% of Malagasy people live in rural area where agricultural activities are performed on different landscapes (Forest, Coast, plains, shrubland). Nevertheless, due to the unsustainable agricultural practices (slash and burn, imbalance fertilization…), add to the spectacular erosion phenomena, Malagasy soil undergoes a considerable pressure. This makes us focus on soil inventory and mapping.

- **The history of soil survey**

Soil research in Madagascar included three major periods (Feller et al., 2010):

- before 1970, French researchers from Office of Scientific Research in Overseas Territories (ORSTOM) particularly worked on the identification of existing soil types, their classification following the French Commission of Soil Science and Soil Mapping (CPCS, 1967)), their spatial distribution in some coastal area of interest, and the study of pedogenesis.

- between 1970-1994 : during which Malagasy researchers from the National Agricultural Research Institute (FOFIFA) and French researchers from ORSTOM have done many works in applied pedology and large-scale mapping of soil type (1 :10,000 to 1 :200,000) for irrigation, fertilization studies and land development.

- and from 1994 : where other overseas researchers (British, Japanese…) joined the Malagasy researchers from FOFIFA and Laboratory of RadioIsotopes (LRI) of University of Antananarivo, and French researchers from the Institute of Research for Development (IRD, formerly called ORSTOM), in soil survey in the framework of climate change mitigation and adaptation, food security, biodiversity conservation, and land degradation.

Maps of 1:200,000 only cover 20% of the national area and the remaining larger-scale studies don't cover more than 2% of the territory. Nevertheless, Soil Organic Carbon (SOC) as the main content of soil organic matter was always considered. Actually, knowledge of the size, the temporal and spatial distribution of SOC sequestration provides a good understanding of the ecosystem carbon balance. This last contribute to a better policy decision making and implementation of a sustainable crop production, and also a sustainable natural resource management.

- **A national database as a main output of soil surveys**

Following the different works of the three above-mentioned periods, a national georeferenced soil and environmental database named VALSOL-Madagascar was established, which contains soil maps and soil data information from soil surveys. This database, updated during the last 5 years by LRI and IRD teams recorded soil information by profile (soil profile (Fig.2 (f) to (i)), including geographical location, physical and chemical soil properties such as soil thickness, soil organic carbon content, bulk density, clay, silt, and sand content, pH (47 properties), …. (Beaudou and Le Martret, 2004).

Now, this database contains 770 soil profiles information carried out by the research during the ORSTOM period and 3,122 soil profiles collected during the third period.

- **Mapping of Soil Organic Carbon**

Many efforts were made in order to acquire good knowledge of the spatial distribution of SOC; they included field works (Fig.2j) all along the big island, and laboratory works (Fig.2 (l) to (o)). This last combines conventional methods with chemical analysis using several reagents and also alternative methods corresponding to the Infrared Spectroscopy (the near- and mid-infrared spectroscopies (Fig.2k) ones). All this allow the establishment of Soil Organic Carbon stocks (SOCs) map at different levels according to the needs of scientists and policy makers (Fig.2). Few attempts were undertaken in SOCs mapping at different level: local, regional and national. At local level, there is the research carried out by Razakamanarivo et al. (2011) on SOCs mapping for the first 30 cm depth in eucalyptus plantations (30 m resolution) in the central highlands of Madagascar by using the gradient boosting model (n = 41 soil profiles). At the national level, Grinand et al. (2009) has produced a SOCs map for the 30 cm depth (1,000 m of resolution) according to VALSOL-Madagascar which gathered SOCs data collected before 1979 (n = 279 soil profiles), by using average values of soil-vegetation units. This study was the first evaluation of organic carbon resource in Madagascar in order to assess its future trend in climate and land use change. At regional level, SOCs mapping of eastern humid ecoregion was done in 2014 (www.perr-fh-mada.net/) by using an updated database (n = 733 soil profiles) of VALSOL-Madagascar at 0 to 30 cm depth (30 m resolution) to the reference level of the greenhouse gas (GHG) emissions from deforestation within this ecoregion (using the Random Forests Approach). Despite these studies, SOCs mapping approaches in Madagascar still need to be developed in order to reduce uncertainty regarding the accuracy of the map. This main uncertainty is often related to sample small size and sample plot location, undersampled locations, errors generated from laboratory analysis and land cover mapping from remote sensing, modelling errors, … . My ongoing research focuses on this problem of accuracy.

- **Towards a digital map of soil carbon at the national level**

In 2015, VALSOL-Madagascar was updated. My main work consists in the capitalisation of these data and producing maps with a minimum of uncertainty at the national level by using easy-to-access covariates in time and in space. The first results showed that the most recent soil inventory (n= 1,993 soil profiles (**Fig.1**) sampled between 2010-2015) with using the Random Forests approach gave a good prediction (R^2 = 0.59 and a RMSE = 25.81 MgC.ha^{-1} on an external validation dataset (n=358)). The model is influenced by elevation, temperature and vegetation data. The SOCs map ranged (**Fig.3**) from 28.3 to 197.6 MgC.ha^{-1} on 30 cm of depth. The total SOCs was 4,137 ± 1,214 TgC with coefficient of variation (CV) of 29%. In spite of this first success, there were some gaps in regions with lithic raw mineral soils because of the lack of our SOCs database and 3.4 % of the area was not predicted. The new national map produced with my model has improved the accuracy of the prediction: (i) in resolution, from the 1km² resolution m for Grinand et al. (2009) to 30 m × 30m in the new digital map (case of county of Didy in **Fig. 4**) and (ii) in value by also decreasing the CV of the maps (66% for Grinand et al. (2009)). Although the accuracy of the map is updated, the next step of my PhD will concern the decrease of uncertainty by testing additional relevant covariates derived from remote sensing dataset.

- **Conclusions**

More than one century of soil studies allowed the IRD and LRI team to achieve the actual stage of spatial distribution of SOC in Madagascar. The use of DSM approach during the last

Fig.2.Challenge in soil sampling for agronomical and environmental research

(Photos N. Ramifehiarivo, N. Ramboatiana, M. Razafindrakoto, A. Rina, N. Rakotovao)

5 years revolutionized the soil research, but much remains to do for achieving efficient national soil research goals in terms of : soil sampling, capacity building in modelling, in data mining and analysing library of spectral data, in producing more interactive maps for the users (mapping of nitrogen and phosphorus for agronomic purposes) and the governments. Despite these studies, soil inventory is far from complete, because of access difficulties on the field work and the relative large size of the country, therefore, networking and advising are always welcome.

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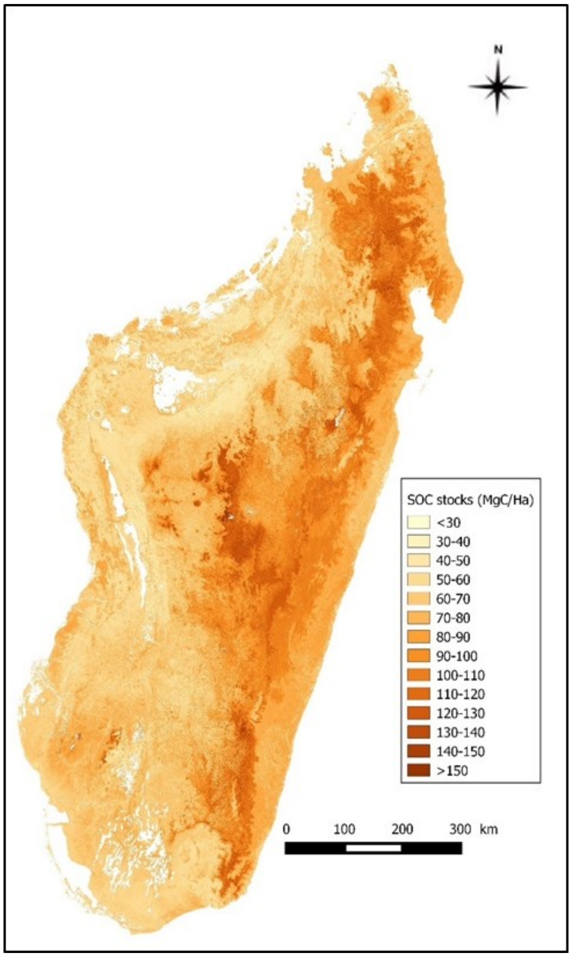

Fig.3. SOCs (MgC.ha^{-1}) distribution map at national scale for the first 30cm soil layer based (2015)

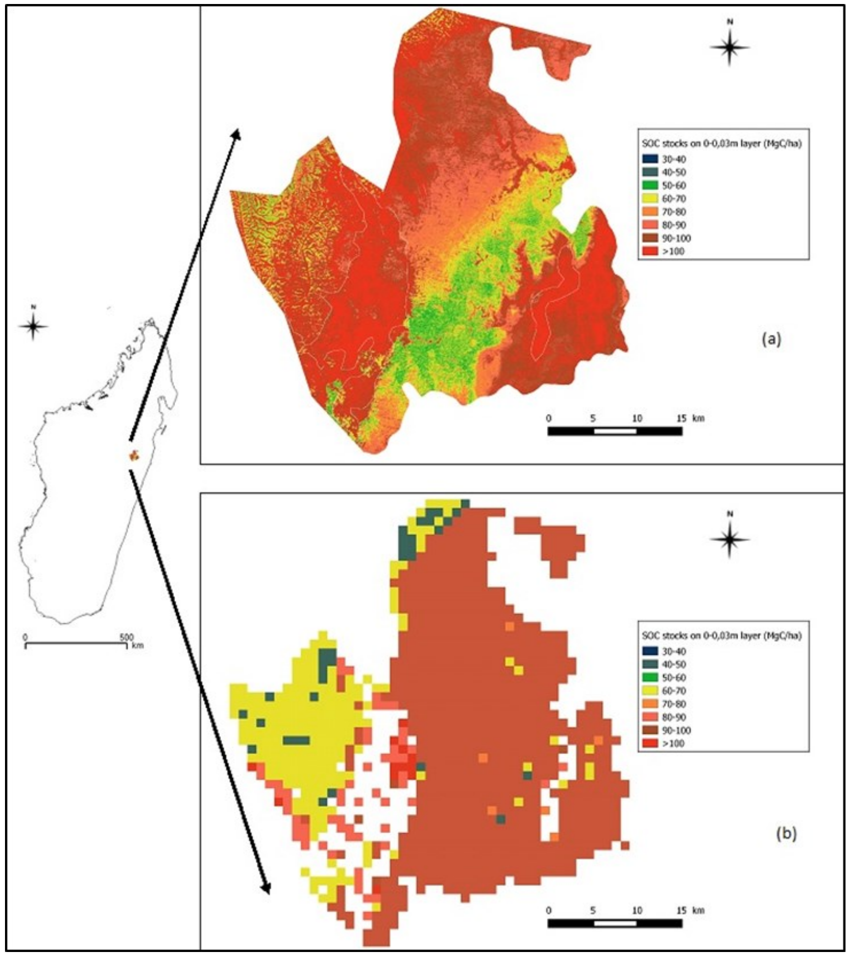

Fig.4. Comparison of SOCs map for the first 30 cm layer in the county of Didy according the new national map (30m ×3 0 m of resolution) (a) and the national map by Grinand et al. (2009) (1km² of resolution) (b)

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Ramifehiarivo Nandrianina is a PhD student at the Laboratory of RadioIsotopes (LRI) of the University of Antananarivo (http://www.laboradioisotopes.com/), Madagascar. His research interests are: soil science, DSM, remote sensing, agronomy and Environment.

Herintsitohaina Razakamanarivo and Michel Brossard are Nandrianina's supervisors and they have closely followed the history of soil survey in Madagascar. Three of them are working closely with other IRD UMR Eco&Sols members, UMR Espace-dev, FTM, ETC-Terra Madagascar and Conservation International Madagascar.

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IN THIS ISSUE

From the Chair

Dear Colleagues

It is a pleasure to present Issue 39 of Pedometron.

This year has been a busy and also a rough ride, and some said that it opens a period of uncertainty.

Maybe it is time for pedometricians to tackle more uncertainty, as Claude Shannon once said, “Information is the resolution of uncertainty”. Thus Pedometrics will keep working to resolve this issue.

The Pedometrics commission continues with the annual Best Paper award nomination. Please read the nominated 2015 papers, and vote for it. As a result of the meeting in Cordoba last year, we now officially has the Margaret Oliver Award for early-carreer pedometricians. Nomination is now open.

We will be celebrating 25 years of Pedometrics in 2017. The first Pedometrics conference was held on September 1-3, 1992 at Wageningen. And the first official publication was published as a Special Issue of Geoderma (1994, Vol. 62, Nos. 1-3: 1-326). Pedometrics was established as a provisional working group of the ISSS in 1988.

I hope to see you all next year in this exciting meeting. The organising committee promises for an exhilarating adventure.

Sydney, November 2016

Budiman Minasny