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RESEARCH PROJECT TITLE: Use of Electrical Resistivity and Self Potential Mapping for Sustainable Agriculture: Application to Rubber Tree Plantations in North-East Thailand

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   [X] Executive summary
   [X] Acknowledgment
   [X] List of collaborating Thai researchers and/or Thai institutions
   [X] Background and rationale
   [X] Objective of research
   [X] Research methodology
   [X] Research results
   [X] Conclusions and recommendations
   [X] References
   [X] Appendices (*if necessary*)

I do hereby certify that all of the above given checks are true.

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2 February 2016
(Date)

Executive summary

In the North-East region of Thailand, where the climatic conditions and soil properties are not well adapted of the rubber tree cultivation, it is very important to develop and apply a strategy of sustainable agriculture allowing on the one hand ensure a good yield, and on the other, to preserve the soils against erosion and degradation. Detailed knowledge of the soil spatial variability and monitoring the temporal evolution thereof are fundamental for implementation of this approach. Traditional soil management and intensive cropping in this area should include specific studies on soil-water-plant-atmosphere interactions. The increase of the surfaces of rubber-tree plantings in the long term can lead to important changes of water resources and unforeseeable impact on soils. The sandy soils, which are widespread in this region, are characterized by light structure, and their low contents of organic matter and clay. The weak cohesion between grains in the structure of sandy soils makes them very vulnerable against hydraulic (run-off or leaching during infiltration) erosion and crusting development.

The conceptual framework of this project is deepening knowledge on physicochemical properties and hydro-structural functioning of the soils by applying different geophysical methods coupled with traditional approaches of soil sciences.

The studies were carried out on the experimental site of "Ban Non Tun" representing a rubber tree plantation, which is located at 15-20 km south-south-west of Khon Kaen city. An agronomic trial was implemented on this site in form of plots of various plants at different levels of the slope with the aim to protect the soil against water erosion by covering the bare surface. At the same time, these plots, installed in the inter-rank areas, were used to assess the influence of nitrogenous enrichment (plots of ***pueraria***) in a natural way on the growth of trees, and evaluate the impact of plants with deep and well developed root system (plots of ***vetiver***) on the water infiltration rate.

In order to study the soil spatial variability on the experimental site "Ban Non Tun", the geophysical maps was carried out using the of Spontaneous Potential (SP) and Electrical Resistivity methods. The measurement protocol and the device with different spacings between the electrodes, which were used in the mapping of the apparent electrical resistivity, have allowed obtaining three maps corresponding to 3 different depths of investigation.

Comparison of the spontaneous potential (SP) map with the one of the apparent electrical resistivity (ρ_a) corresponding to the most superficial part of soil showed a very good coherence between anomalies corresponding to the same locations on the site. The highly localized conductive anomalies correspond to the strongly negative SP anomalies. The observation in the same places of negative anomalies of the spontaneous potential and low values of electrical resistivity usually indicates the presence of wet clay in the soil. This assumption was confirmed

by the results of auger soundings. In addition, the results of these analyses indicated relationship between the intensities of geophysical anomalies and the soil clay contents.

The apparent electrical resistivity maps, particularly those corresponding to the shallow part of the ground, showed easily noticeable highly resistant anomalies extending along the tree ranks. It was not possible to link these anomalies directly to the root systems of trees because of the differences in topographic elevation between the "tree ranks" and "inter-rank spaces". These topographical unevennesses were specially created to protect trees roots from water excess during rainy periods. In fact, the topographic irregularities may themselves generate apparent electrical resistivity anomalies, even in a homogeneous underground. To understand the nature of these anomalies and to estimate the contributions of various sources, I proposed an additional NRCT project for the internship of a Master 2 degree French student (Mr.Sylvain Pasquet) in Applied Geophysics, which I supervised with my colleagues from LDD (Khun Nopmanee Suvannang and Dr. Rungsun Imerb). Detailed analysis of the geophysical prospecting results and numerical modeling, performed during this project, allowed us to estimate the impact of the "topographic effect" on the measured values of apparent electrical resistivity and has shown that these extended resistant anomalies can be primarily related to the land management works. Raised parts of the relief, corresponding to the tree ranks, were created by extracting the soil in the "inter-rank" areas to transfer it on the lines of trees. These works certainly led to a significant degradation of the structure of these soils, which could mainly result in an increase of their electrical resistivity. (Pasquet, 2011). This work has also shown that the measurements are less influenced by topographic irregularities when using the configuration "pole-pole" electrode, which we used during the electrical resistivity mapping.

The site-wide spatial variation of considerable intensity of the electrical resistivity, with a large resistant anomaly corresponding to the diagonal and to the south-eastern part of the planting, is certainly caused by the differences of soil characteristics. Comparison of electrical resistivity maps with the results of agronomic observations, like the tree girth, showed a general pattern of relatively high growth of trees in areas where the values of electrical resistivity are higher. Particularly, the rubber trees planted in the plots of ***pueraria*** are mostly characterized by large diameters. This high growth is probably linked to the high concentration of nitrogen in the soil, following agricultural trials. In the relatively conductive areas, the tree growths were very low, and the trees were missing in areas representing the highly localized and quite conductive anomalies. In these areas the trees were dried even after their replanting.

On this site the natural growth of trees has been disturbed by water stress after a prolonged drought during the period from October 2009 to June 2010. In July 2010, an observation of the state of each tree was conducted to evaluate the caused damages. So, the comparison of the results of this observation with the apparent resistivity map showed that the severely damaged trees were located in the less resistant areas, and in the two plots of ***pueraria*** located further south. In this not single case, from the point of view of interaction between the plant and the soil with a low humidity, the normal functioning of the roots of trees can be disturbed by the high capacity of water retention by clays. The large number of damaged trees on ***pueraria*** plots was certainly result of the strong competition between the roots of the two plants (***pueraria*** and ***hevea)*** under low humidity conditions and small thickness of soil. Electrical resistivity tomography revealed that the soil thickness is greater in the plot of ***pueraria***, located in the North of the site. The downstream position of this plot with more favorable conditions (water content, thickness and texture of soils) to the growth of rubber trees also explain the greater resilience of trees and other plants in this area against the water stress.

The consistency between the results of agronomic observations, soil surveys using traditional methods and spatial variations of geophysical parameters show the importance of inter-disciplinary studies. These results demonstrate the sensitivity and effectiveness of geophysical parameters (like electrical resistivity and spontaneous potential) in the study of the spatial variability of soil characteristics, and the understanding of interactions "soil-water-plant-atmosphere". The analysis of the overall results of the geophysical and agronomic observations exposes clearly the influence of the spatial variability of soil on the growth of trees and the functioning of the root systems of plants. At the same time, these results also reveal the impact of agricultural trials on soil characteristics. In specific climatic conditions in NE Thailand with lack of sufficient moisture for rubber-tree growth, the water and nutrients availability in soil are very decisive factors not only for latex production, but also to ensure inter-rank crop yield.

Acknowledgment

I express my gratitude to NRCT for evaluation and acceptance of my proposal for this research project that allowed its implementation and its achievement in Thailand. I am also grateful for the interest about this study and for the acceptation of this report with an important delay, due to my unexpected and very sudden return to France, which had greatly disturbed my use of time and had bothered me to finish and submit the complete report.

I am grateful for the administration of Land Development Department (LDD), our colleagues from Office of Science for Land Development and from Region 5 (Khon Kaen) of LDD for their hospitality, their fruitful collaboration and valuable consultations that have greatly helped me to achieve this project.

I would like to thank Prof. Sayan Sdoodee, from Prince of Songkla University (PSU), Faculty of Natural Resources, Department of Plant Science and Dr. Vidhaya Treloges from Khon Kaen University (KKU), Faculty of Agriculture, Department of Soil Science, for their interest shown towards this project. Their highly targeted issues helped me to adjust certain aspects of my work and make it useful in order to meet the challenges of agriculture practiced in Thailand.

I am also grateful to the owner of the rubber tree plantation, where located the experimental site "Ban Non Tun", for permission to conduct geophysical prospecting in the plantation.

My thanks to all Thai and French students (Master and Ph.D. degrees) with whom I had the pleasure to meet, teach and train them on the different experimental sites, for their great interest towards to the field of my scientific researches (Applied Geophysics).

Finally, I express my thanks to all IRD assistants for their constant availability and their ability to find solutions in specific and not easy situations. I would like to express my special thanks to Khun Worraphan Chintachao and Khun Ratchapol Siriboon, who accompanied me during all the missions, their desire to learn and improve the quality of daily provided work have increased too my motivation and have greatly contributed in achieving of this project.

List of collaborating Thai researchers and/or Thai institutions

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Background and rationale

The population and economic growths of Thailand demand a constantly growing need for land, including agricultural land. Following its establishment in 1963, the Land Development Department (LDD) started to combat land degradation. LDD's activities are based on increasing the yield per unit of land area instead of expanding cultivated areas by deforestation. Currently, the production of natural rubber has become an important economic asset for Thailand because it generates considerable revenue for all workers in this field of activity. Since 1991, Thailand has been the largest producer and exporter country of natural rubber in the world. Each year it exports about 1.6 million tons of this product. More than 80% of Thailand natural rubber is produced by smallholders. Natural rubber is produced thanks to the collected sap (known also as latex) of the Pará rubber-tree. Initially, this tree (called *hevea brasiliensis*) grew only in the Amazon rainforest. The ideal climatic and environmental conditions for the Hevea correspond to this area, i.e. mean annual temperature of 26°C ± 2°C, and high rainfall (from 1800 to 3000 mm/year) well distributed throughout the year (with 120 - 240 rainy days per year) [Gonçalves & al., 1999]. At the end of 19th century, with world industry developing and due to an increasing demand for the commodity, the rubber-trees were exported and spread extensively in other tropical regions.

At present, LDD's strategy includes rehabilitation of marginal up-lands of North-East (NE) Thailand in order to enlarge the area of rubber-tree plantations and to improve living conditions for Thai smallholders. This region is characterized by a semi-arid tropical climate where the annual mean air temperature is 26°C and the total precipitation does not exceed 1300mm/year, almost all of which falls in the rainy season from April to October [Watanabe & al., 2004]. If the temperature is favourable for rubber-tree growth, the rainfall remains below the requested moisture and is not distributed regularly. The effects of water deficiency or excess can lead to reduced rates of tree growth, low latex yields [Rao et al., 1998], and in severe cases, the water stress may affect the plantations resulting in Hevea diseases, such as Trunk Phloem Necrosis [Nandris et al. 2004] and total crop failure.

By taking into account also the fact that the sandy soils in this area are not rich in organic matters and other nutrients, the soil and the climate can be considered as marginal for rubber-tree and for other plant cultivation. Traditional management of intensive cropping in this area should include specific studies on "soil - water – plant – atmosphere interactions". Failure to do so could cause irreversible damage. Particularly, inter rank crop plantation within the young rubber-tree seedlings is already being experimented on in North-East Thailand by small holders to ensure incomes during the period until rubber production starts [Kunalasari 2006]. These inter rank crops, on the one hand, could protect soil against run-off and splash erosion

[Valentin 2004, Viswanathan et al., 2006], but, on the other, these plants can be in competition with rubber tree roots for moisture and nutrients in the soil. It should be noted that an increase in area of rubber tree plantings in the long term can lead to significant changes in water resources and to unpredictable impact on soils.

Since 2007, these issues have been presented in a TICA project of LDD named: "Impact assessment of planting rubber-trees on sandy soils in NE Thailand" which has presently been accomplished with the assistance of IRD scientists. Amongst various objectives, one of the results awaited from this TICA project is a noticeable water table drawdown and a surface runoff reduction in up-lands, thereby decreasing the artesian pressure in the low-lands. The consequences of these phenomena must be thoroughly studied, followed and estimated. This project was integrated in the TICA project to reinforcing and enlarging studies by applying different geophysical methods.

A soil may be presented as a natural organized product, resulting from the interplay of the soil-forming factors: parent material (rocks), climate, hydrological and biological functioning, topography, and time. Most of the processes involved in soil formation, presented by physical, chemical and biological interactions between inorganic and organic parts of the medium, occur in every soil but their importance and intensity are not the same everywhere. During the soil evolution, these differences can result in soil heterogeneities. Thus, the physico-chemical features and behaviours of soils can vary in a wide range of scale, from a regional one to very localized small areas. The phenomena in this complex environment are numerous, and many of them are not sufficiently studied or understood [Ta-oun et al., 2005].

These heterogeneities, presented as soil spatial variability, can be revealed and studied by detailed geophysical surveys using electrical resistivity and Spontaneous Potential (called also Self-Potential) methods. It is already established that electrical resistivity of soils depends on their other physical and chemical properties (morphology, texture, water and clay contents, salinity, etc...) [Samouëlian et al. 2005; Tabbagh et al. 2000]. Electrical apparent resistivity mapping, supplemented by the results of spot observations using traditional methods of Soil Sciences, and coupled with statistical analyzes can greatly increase the accuracy in determining the limits between units of different types of soil [Moeys et al., 2006]. Mapping, when used a constant distance between electrodes serves to evaluate the heterogeneities of soils in the horizontal plane with a more or less constant depth, knowing that a larger gap between the electrodes increases the depth of investigation. In some situations, the method of 2D ERT (2 Dimensional Electrical Resistivity Tomography) is used along a line with the aim to obtain the distribution of electric resistivity values in vertical plane (transect).

Self-Potential (SP) method application enables to measure natural electrical signals on the soil surface, which are usually generated in a porous media by electro-chemical phenomena such as: oxidation-reduction and electrokinetic phenomena (streaming potential and sedimentation potential), diffusion-adsorption processes caused by the differences of ion concentrations [Hovhannissian et al., 2002; Pinettes et al., 2002; Pozdniakova et al., 2001; Ernstson & Scherer, 1986]. Self-Potential method coupled with electrical resistivity measurements provides means to describe the subsurface properties without digging, to oversee textural and structural features of soil, to monitor spatial and temporal dynamics of moisture and nutrients in the soil.

In the TICA project of LDD, which is already in process, the usual methods have been used. The measurements of water content variations are carried out on selected soil samples. The underground water level studies have been performed in boreholes. These observations characterize only separated points or very localized areas.

Compared to traditional soil science methods, geophysics is nondestructive and allows studying large areas quickly and in detail from the surface measurements without digging. Because the electrical resistivity and self-potential are very sensitive to the changes of different soil properties, these methods can be efficiently applied to: soil type differentiation, monitoring of water and clay content variations, delineating infiltration, underground flow and matter transfer areas [Brevik et al. 2006, Samuelian et al. 2005, Anderson-Cook et al. 2002, Doussan et al. 2002, Tabbagh et al., 2000].

Objective of research

The main objectives of this project are:

A. – Detailed self-potential (SP) and electrical resistivity mapping to investigate soil spatial variability in order to establish links between specific characteristics of soils, such as texture, structure, hydraulic permeability, clay content, water holding capacity, and measured geophysical parameters.

B. – Surveying the evolution of measured geophysical parameters on various types of soils with different inter-rank crop plants compared with water dynamics to understand hydro-structural functioning of the medium in different conditions and to assess their effect on the rubber-tree growth, as well as on the inter-rank crop yield.

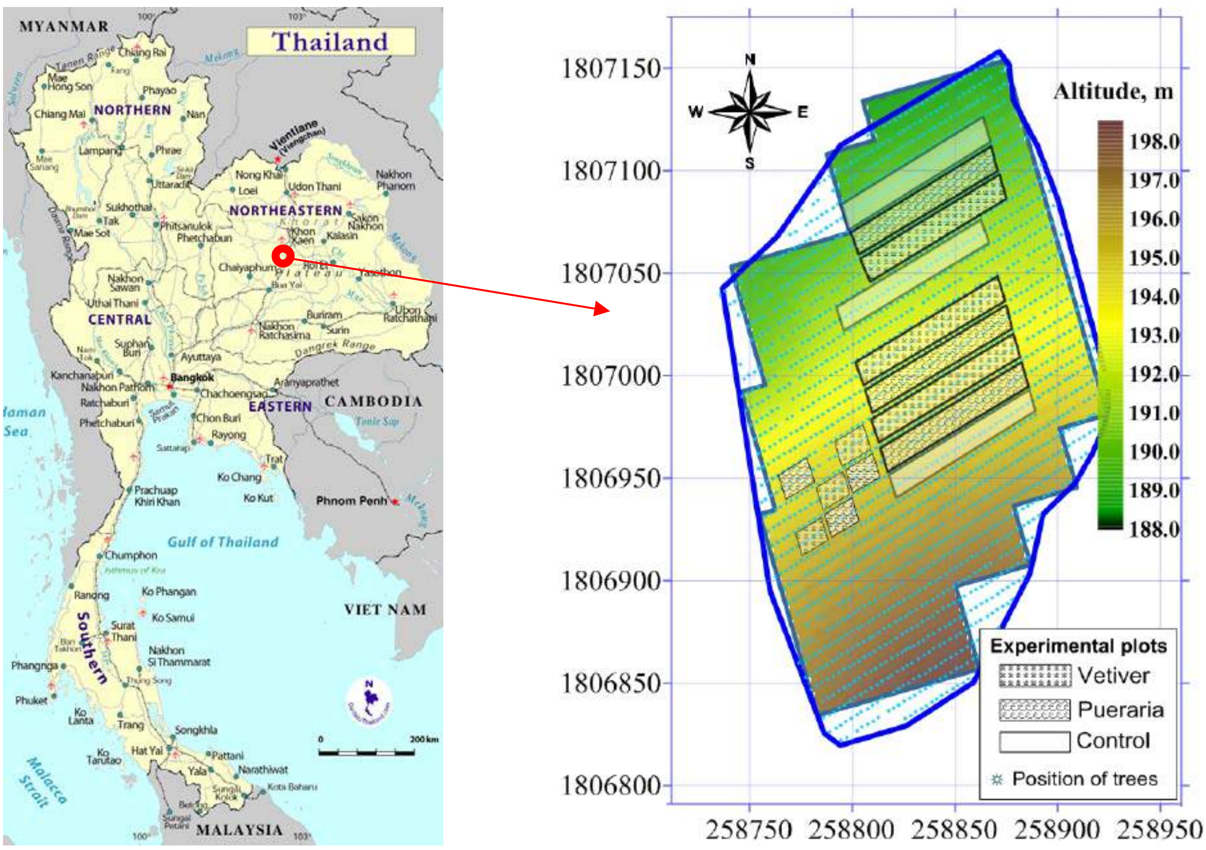
C. – Elaborating appropriate techniques of soil and water preservation. Conceiving reliable methods for variable rate of fertilizer use on the basis of obtained results on properties and behaviours of different soil types.

D. - Teaching and training of local staff on applied methods and technology.

Research area: description of the *experimental site "Ban Non Tun"*

The experimental site of "Ban Non Tun" is located about 20-25 km southwest of Khon Kaen city (Fig. 1a) and covers an area of 3.75 ha. The surface of this site has a form of an irregular polygon with corner coordinates: (48Q258740E, 1807050N; 48Q258795E, 1806810N; 48Q258860E, 1806840N; 48Q258930E, 1806985N; 48Q258865E, 1807190N) in the UTM (Universal Transverse Mercator) geographic coordinates system.

The difference in altitude, between the southern (upstream) and northern (downstream) parts of the site is slightly more than 10 m, with main slope about 2-5%, oriented approximately South-North over a length of 250-300 m. In topographical terms, the ground surface is convex with the central part higher (from 0.4 m to 0.9 m) relative the lateral areas (Fig. 1b). The used equipment (Nikon Total Station – DTM - 332) and the applied methodology have allowed us to obtain sufficient accuracy and to establish horizontal coordinates (X and Y) with errors less than ± 0.10 m and, to define the altitude Z with uncertainties smaller than ± 0.05 m. The topographic map of the experimental site was performed with a spatial resolution of 4m x 1m on the 75% of the site area, and 2 m x 1 m, for the remaining 25%.



a. b.

Fig. 1 Location (a.) and topographic map of "Ban Non Tun" experimental site with the positions of crop plots (b.)

The results of morphological studies in "Ban Non Tun" experimental site showed that shallow soils have a texture from fine sand to loamy-sand. Soils become clayey from about 1m depth, except in some areas, where the soil contains clay starting from 0.4 - 0.6 m depth [Siltecho et al., 2010]. According to results of this study, the soils in this site are characterized by very low (less than 1%) organic matter content and relatively significant acidity (pH is around 5).

This site presents an experimental planting of rubber tree, where the trees are being planted every 2.5 m along the lines (called "ranks") with a distance of 7 m between the "ranks." The altitudes of ranks are slightly (0.25 - 0.5 m) higher compared to the "inter-rank" areas. These topographic structures were created with the aim to protect tree roots from water excess during the rainy season.

At this site, an agronomic experiment was performed to investigate the effect of land use with the introduction of perennial crops on the quality of soil, serving as reservoir of water and compartment of nutrients, which are essential substances for plant growth. To this end, the plots of ***Pueraria*** and of ***Vetiver*** have been installed in selected "inter-rank" areas (Fig. 1b).

These crops were cut regularly and were spread on the surface of corresponding plots as mulch, in order to provide high amounts of aboveground biomass. The plots of ***Pueraria*** have aimed to naturally increase the nitrogen content and fix it in the soil during the plant degradation and exchanges between crop residuals and soil. The ***Vetiver*** plots were used to reduce the impact of water excess in the soil, due to very long roots of this plant. The incorporated residues and the residual roots could serve as important channels that facilitate the coming of surface water into the ground. The vegetal covers of these plots could also offer a protection to the soil surface against wind and water erosion [Willey, 1979; Lal, 1989ab; Lesturgez et al., 2004].

Research methodology

During prospecting of "Ban Non Tun" experimental site we used three geophysical methods:

A. Spontaneous Potential (SP) mapping
B. Electrical Resistivity (ER) mapping
C. Two Dimensional Electrical Resistivity Tomography (2D ERT)

A. Spontaneous Potential mapping methodology and equipment

Self Potential or Spontaneous Potential (SP) method is founded on the studies of natural or spontaneous electric potentials principally generated in the ground by physical and electro-chemical phenomena (electromagnetic induction, thermal and pressure gradients in underground fluids, variation of the mineral content in medium, redox and electrokinetic phenomena, diffusion-adsorption processes in the contact zones, bioelectric activity of organic substances, etc...). The application of this method is simple, fast and particularly useful in rapid recognition of the heterogeneities in the superficial part of the ground.

During self potential measurements it is not possible to use metallic electrodes because electrochemical interactions at the ground contact would create spurious potentials due to electrodes polarization. Moreover, these contact potentials are quite erratic in different types of soil and cannot be corrected. Consequently, the use of non-polarizable electrodes is absolutely essential. These consist in avoiding direct contact between bare metal and ground. A non-polarizable electrode is typically made of a metal rod immersed in a plastic container filled with a saturated solution of its own salt. At its base, the container has a porous part, which is saturated by electrolyte and allows create a contact between metal and ground through the solution, proved non-polarizable. For the measurements we used "lead - lead chloride" (Pb-$PbCl_2$) non-polarizable electrodes. Their stability and efficient performance are confirmed during numerous experiments.

To create a good contact between electrode and ground, we have cleared the vegetation of this place. In addition, to improve these contacts, the electrodes were installed in holes usually 10-15 cm in diameter and with depth of 10-25 cm. Depth varies from one measurement point to other, because it is always best to go below the roots of plants to avoid the influence of electrical potentials associated with biological activity (Fig. 2). Also note, that in depth the soil moisture increases, which reduces the contact resistance between the electrode and the ground.

Fig. 2 Implementation of the measuring electrode in the hole

During self-potential mapping we applied the technique called "measurements with fixed base" or "measurements with referenced electrode". To apply this implementation, one of the electrodes pair should be installed in a fixed base station located outside the study area. The electric potential difference measurements at the ground surface are carried out between this reference electrode and the mobile electrode, which is moved on regular grid points to cover the study surface. The distance between measurement points defines the spatial resolution of the SP map.

A voltmeter, which I especially designed and made for self potential measurements, was employed. This voltmeter is characterized for its high input impedance (10^9 Ohm) and a good sensitivity (10^{-5} V) (cf. Fig. 3). It is equipped with a low-pass filter that allows register only the electrical signals of frequencies below 1Hz.

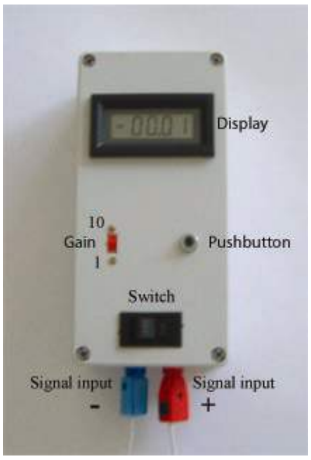


Fig. 3 Voltmeter with high input impedance used for SP measurements

By convention, the reference electrode is connected on the negative input contact of the voltmeter and the mobile electrode is connected with the positive one. As the measured values are relative to the potential of reference electrode, it is obvious that with another "fixed base" the contours of equipotential lines would be the same ones, only the absolute values of the potential differences would be shifted by a constant value. Thus, the normalized results are generally presented on the map.

B. Electrical resistivity mapping and used equipments

Measurement of electrical apparent resistivity (ρ_a) requires four electrodes: two electrodes (called "current electrodes or C_1 and C_2") are used to inject in the ground an electrical current of controlled intensity (I), and between two others (called "potential electrodes or P_1 and P_2"), the resulting difference of electrical potential (ΔV) is measured. The electrical apparent resistivity is calculated by following formula, derived from the Ohm's law:

$$\rho_a = K \cdot \frac{\Delta V}{I} \qquad (1)$$

where K is a geometric coefficient and depends on the configuration of four electrodes.

The value of K can be defined by using following formula:

$$K = \frac{2\pi}{\frac{1}{C_1P_1} - \frac{1}{C_1P_2} - \frac{1}{C_2P_1} + \frac{1}{C_2P_2}} \qquad (2)$$

Here C_1P_1, C_1P_2, C_2P_1 and C_2P_2 represent the distances between corresponding electrodes.

To determine subsurface electrical apparent resistivity distribution in experimental sites we used the so called "Pole-pole" configuration of electrodes, which consists of 2 mobile electrodes (C_1 and P_1) and 2 remote and fixed electrodes (C_2 and P_2) (c.f. schema in Fig. 4). In practice the ideal "Pole-pole" array, with only one current and one potential electrode does not exist. To approximate this array, the second current and potential electrodes (C_2 and P_2) must be placed away from the prospecting surface at a distance of more than 20 times exceeding the maximum separation between C_1 and P_1 electrodes used during the survey.

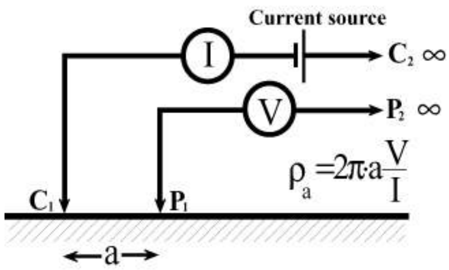


Fig. 4 Schematic illustration of "Pole-pole" electrode array

The use of "Pole-pole" electrode array in mapping is justified because that allows reduce the number of mobile electrodes from 4 to 2, this electrode configuration is very sensitive to vertical heterogeneities and provides deeper depth of investigation.

When this device is used in homogeneous medium each measured value of the electrical apparent resistivity corresponds to a semi-spherical volume localized between the electrodes C_1 and P_1, which means that the investigation depth is roughly comparable to the spacing between mobile electrodes. In this case, the gap "a" between mobile electrodes C_1 and P_1 will defined the depth of investigation, and the geometric coefficient will be determined as: $K=2\pi \cdot a$.

Electrical apparent resistivity measurements have been performed using "Resistance Meter RM-15" combined with a "MPX-15 Multiplexer module" (Fig. 5).

Fig. 5 RM15 Resistance Meter with MPX15 Multiplexer module

To facilitate displacement, the resistance-meter and the multiplexer are fixed on a versatile modular frame system whose basis is a beam of 2 m long, on which 5 stainless steel electrodes are mounted with spacing of: a = 0.5 m (Fig. 6).

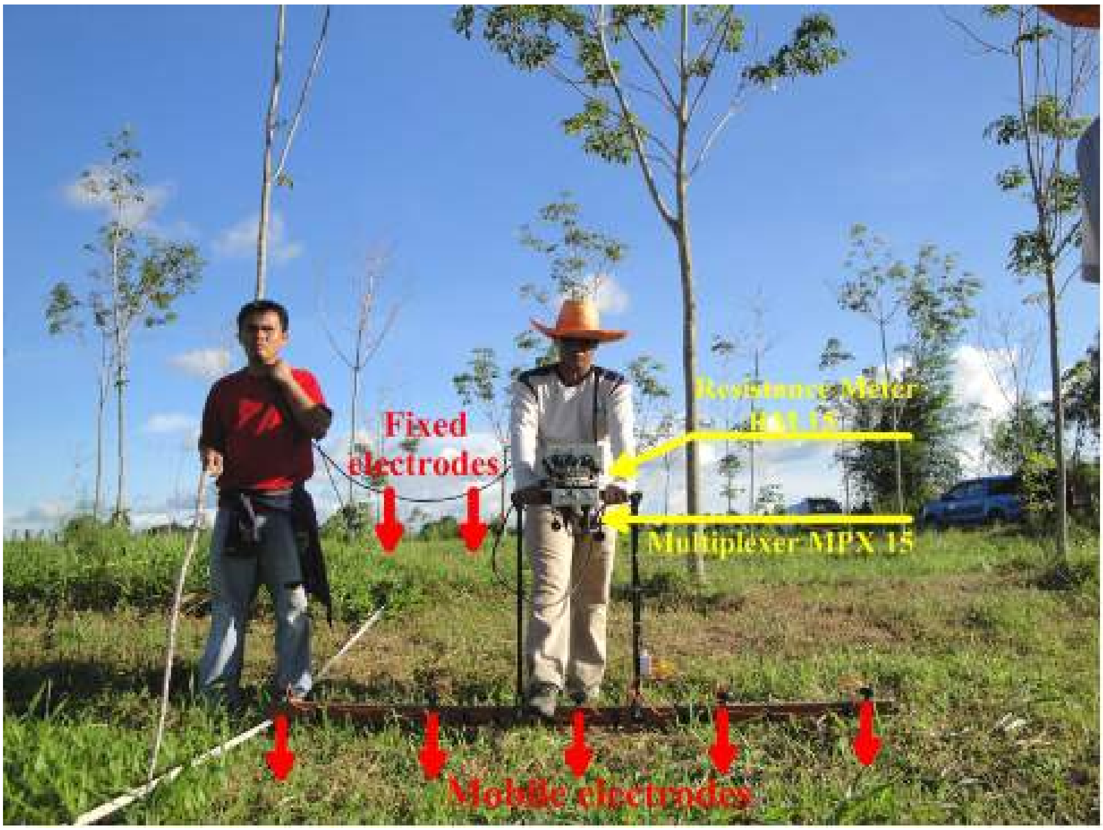


Fig. 6 Electric resistivity mapping device (Resistance Meter RM15 with Multiplexer module MPX15 fixed on the frame) in use on the experimental site

The electrical apparent resistivity measurements were recorded after having created good contacts between the electrodes and the ground. For each position, by using a specific protocol, this device enables to carry out 7 measurements with 3 different spacing between mobile electrodes: 4 measurements with a=0.5 m; 2 measurements with a=1.0 m and 1 measurement with a=2.0 m. During mapping, this equipment was moved by a step of 1 m on a regular grid with georeferenced coordinates. Thus obtained data enable us to represent the results on maps corresponding to three different depths of investigations:

a. - from the ground surface (h=0 m) until 0.5 m,

b. - from ground surface until h=1.0 m

c. - from ground surface until h=2.0 m approximately.

The spatial resolutions of these maps have been defined by the spacing between the mobile electrodes and by the moving step. So, they are: 1m x 0.5m corresponding to depth from ground surface until 0.5 m, 1m x 1m for the map until 1 m of depth and 1m x 2m for the map corresponding to the depth until 2 m approximately.

B. Two Dimensional Electrical resistivity tomography (2D ERT) and used equipment

The use of two-dimensional (2D) electrical resistivity tomography, carried out from the ground surface, under favorable conditions provides the distribution of electrical resistivity values in both the vertical and horizontal directions (geo-electric section of subsurface) along the survey line (profile), on which the electrodes are implanted. On the experimental site "Ban Non Tun" this method was used on a transect along the main topographic slope in order to study the variations in the soil thickness, the distribution of moisture in this compartment and other features that can be useful to understand and to interpret the results of agronomic experiments. To this end, for the measurements we have chosen the electrode array "Wenner-alpha", where the four electrodes (2 for current injection - C_1 and C_2, and 2 for measuring the electric potential difference – P_1 and P_2) are installed with equidistant spacing "a" (Fig. 7). For this array of electrodes the geometric coefficient determined as: $K=2\pi \cdot a$.

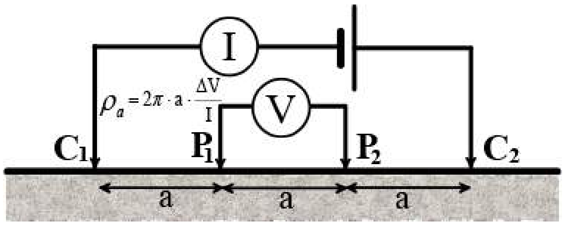


Fig. 7 Schematic illustration of "Wenner-alpha" electrode array

This device is characterized by its sensitivity to the vertical variations of electrical resistivity, and so, it is recommended for studying the horizontal structures. The disadvantage of this device, the shallow depth of investigation, is not very disturbing, because the thickness of soil in this site is relatively small and, in extreme cases, does not exceed the first meters.

The measurements of electrical resistivity are done with Syscal Pro - 72 electrodes, manufactured by Iris Instruments, France (Fig.8).

a.

b.

Fig. 8 Resistivity meter Syscal Pro with multi-core cable (a.) and with subsurface electrical resistivity pseudo-section on the computer screen (b.)

This equipment has an integrated microprocessor system used to install and implement various sequences of measurements. This device can operate independently or with the connecting of a computer.

The typical setup for a 2D ERT survey with 72 electrodes along a straight line, attached to 2 multi-conductor cables, with a constant spacing between electrodes was used (Fig. 9). These multi- conductor cables are connected to the electronic switching unit of the device, which allows automatically select the appropriate electrodes for each measurement following the protocol of the chosen sequence.

For a full 2D ERT image of the subsurface, using the "Wenner-alpha" electrode array, the coverage of the measurements must be completed with the electrode spacings of "1a", "2a", "3a"..."n*a" (Fig. 9). The maximum value of "n" is defined by the total number of electrodes. We don't need to use wider spacings between the electrodes, when the survey layers are not so deep. It should be noted that a larger gap "a" between the electrodes gives a greater depth of investigation.

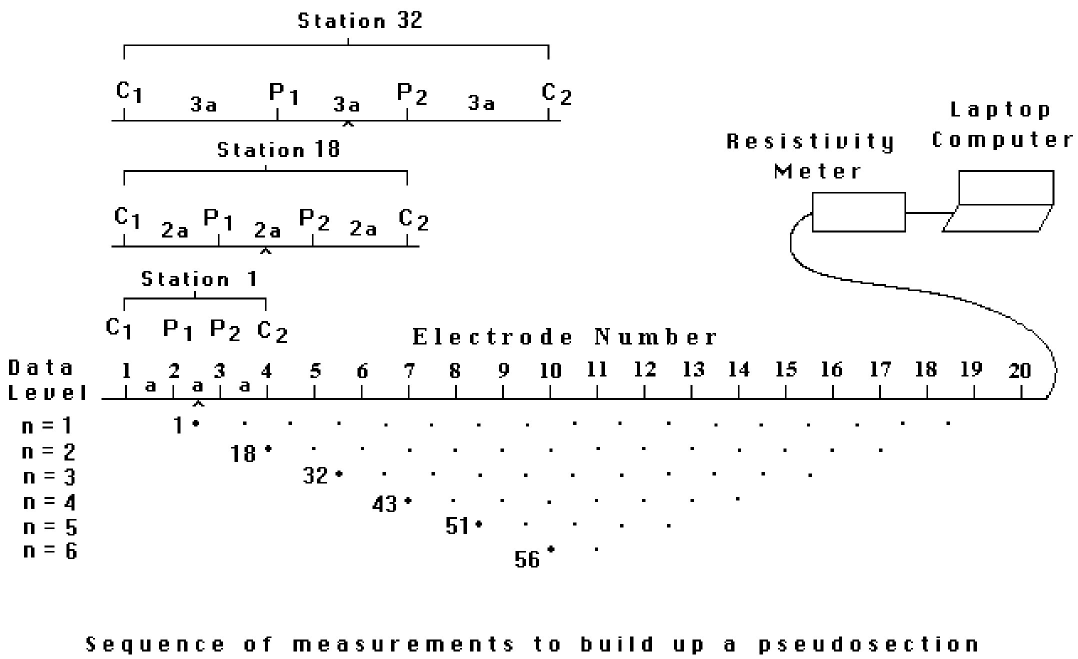


Fig. 9 Arrangement of electrodes for a 2-D electrical survey and the sequence of measurements used to build up a pseudo-section (After: Loke, 2001)

In our case, when used 72 electrodes spaced 1 m on the profile, the sequence was planned to finish the steps to a maximum distance of 12 m between the electrodes, which allowed to have a depth of investigation about 8-9m.

After completing the sequence of resistance measurements, the values of electrical apparent resistivity are automatically calculated and registered in a file. These data are used to plot the 2D pseudo-section using contouring method. On the resulting image, the horizontal location of each obtained value is placed at the mid-point of electrode set, used to make that measurement, and, the vertical location of the plotting point is defined by a special function for different electrode configuration depending to the distance between the electrodes.

The final step of this survey is converting the apparent resistivity values into a resistivity model section that can be used for geological interpretation. For this purpose, the RES2DINV program was used, having a number of settings and options that can be changed, to obtain results that are closer to the underground structures.

Research results

A. Results of Spontaneous Potential (SP) mapping and of auger soundings

Self potential (SP) mapping was performed using the measurements technique relative to a reference electrode (RE). This reference electrode was placed outside the study area, at a distance of 12 m from the southern edge of the mapped zone and at a depth of 25-30 cm. This electrode remained in this place till the end of the mapping. The electrical potential difference was measured between the RE and the mobile electrode, which was moved on the site following a regular grid of 5 m side. As the measured values are compared to the potential of the reference electrode, it is obvious, that using another "fixed base" the contours of the equipotential lines would be the same, only the absolute values of potential differences would be shifted by a constant value. Thus, the normalized values were used to construct the maps, shown in Fig. 10 (a & b).

The choice of the regular grid (5m x 5m) for SP mapping allowed us to perform in total of about 900 measurements (Fig. 10a).

The surface of the mapped zone is around 2 ha, which covers a considerable surface of the agronomic experimentation, subjected to hydrological and pedological studies in this planting of rubber trees (Fig. 10b).

The SP mapping results depict the natural electric field distribution at the ground surface. The dynamic of spatial variations of the normalized values of the observed spontaneous potential are shown on the map like positive and negative anomalies, is ± 70 mV (Fig. 10a). These anomalies can also be generated by different physicochemical phenomena (like: Red-Ox phenomena, electrokinetics due to underground water flow, evaporation, infiltration, or changes of ion concentrations in the soil, etc...) occurring at the ground surface or in the near subsurface between different interfaces: "soil - atmosphere", "soil - water" or "soil - plant". The results obtained by this method, which studies the electrical charges distribution on the ground surface, show the locations of the projections of different electric potential generation sources on the map plan.

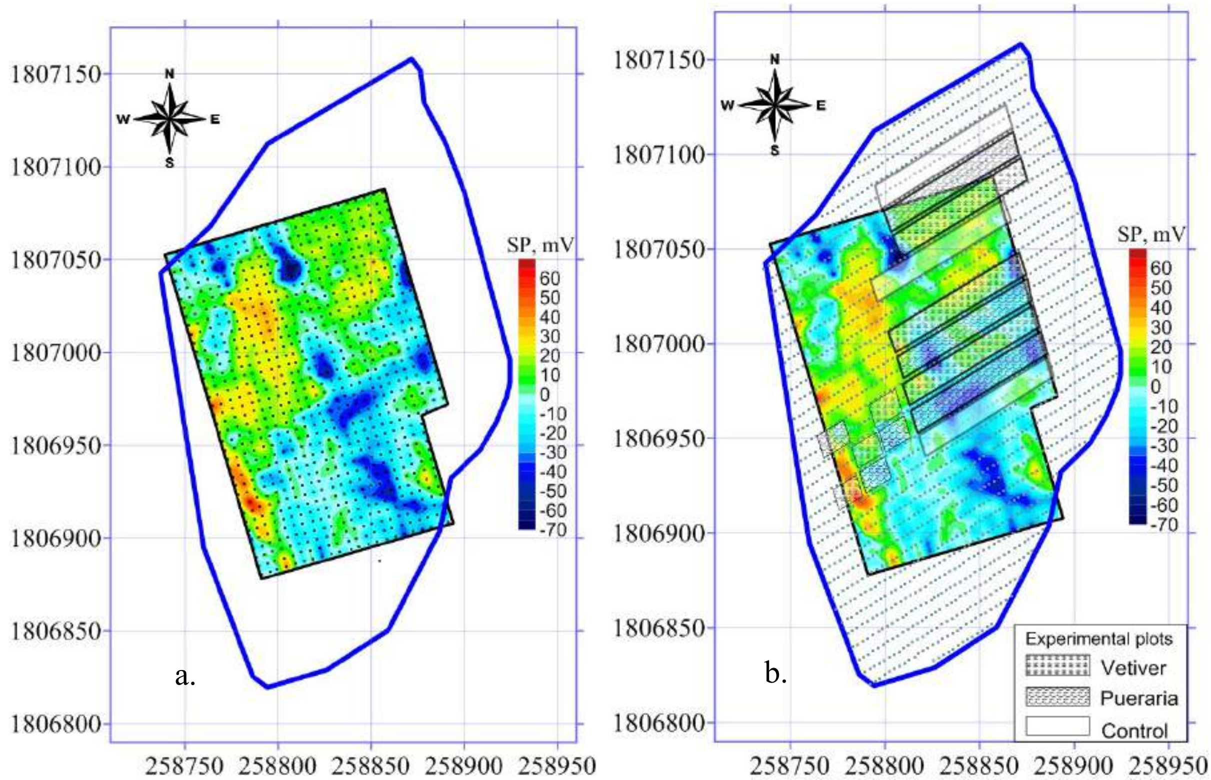


Fig. 10 Results of spontaneous potential mapping of "Ban Non Tun" experimental site:
a. with the positions of SP measurement points
b. with the positions of trees and agronomic experimental plots

An overlay of the SP map with the positions of trees and locations of the experimental plots clearly shows that the plots of Pueraria, located in the south part (upslope) of the site are characterized by negative anomalies of spontaneous potential (Fig. 10b). It is easily noticeable that the northern edge of the large plot of ***Pueraria*** (further east on the map in Fig. 10b), aligned with the rank of trees, which makes the connection with the ***Vetiver*** plot, corresponds also to the limit of the SP negative anomaly. The difference between directions of alignments of tree rows and measurement profiles of the SP (Fig. 10a) shows that this sharp linear boundary cannot be related to the methodology or technique of measurements. The characteristics of negative anomalies, which correspond to plots of ***Pueraria***, show that these anomalies are most likely linked to the agronomic experimental procedure. It should be recalled that the plots of ***Pueraria*** (plant from legume family), have been established with a primary goal to increase the nitrogen content and fixe it in the soil. The role of ***Vetiver*** plots (from grass family) is to minimize the impact of water excess in the soil on the rubber-tree. The presence of these plots with two types of inter-rank plants helps to protect soil against erosion by wind and water.

The SP mapping was conducted during the dry period (end of January early February 2010), which allows us to assume that the evaporation was dominant over other phenomena which could influence the values of the spontaneous potential measurements. From this point of view, the observed positive anomalies probably correspond to areas with higher intensities of evaporation, i.e., to the areas, with high hydraulic conductivity and with low water retention capacity.

It should be noted that the measured value of PS at each point represents the value of integrating all electrical signals, generated by different sources, and its amplitude depends on the intensity and the distance of the location of each source with respect to the position of the measuring point. Therefore, when these results are used alone and separately, it is very difficult, usually impossible, to find a complete explanation about the nature and origins of registered anomalies. In these cases, interpretation of results can be rather phenomenological and qualitative, than quantitative.

The interpretation of SP spatial variations is even more complicated on "Ban Non Tun" site, because the various agronomic treatments and operations on experimental plots alter the initial conditions in the ground. The use of chemicals (fertilizers, herbicides, etc...) changes the chemical composition of the medium and, therefore, the concentration (or distribution) of ions in the soil.

Usually, the SP method is applied in combination with other geophysical methods with the aim to obtaining complementary information in order to facilitate data interpretation.

Soils characterization with auger soundings based on the results of SP mapping

Based on the analysis of the SP mapping results, we conducted surveys by auger sounding to study the spatial variability of textural and morphological characteristics of soils as a function of the natural electric field distribution. This work I did with Dr. Pascal Podwojewski, senior researcher in soil science at the IRD, during his mission to Thailand in April 2010. The locations of auger soundings were selected according to different intensities of self potential anomalies (Fig. 11). In total, we completed 10 soundings extending to the depth of bedrocks, with soil sampling every 20 cm.

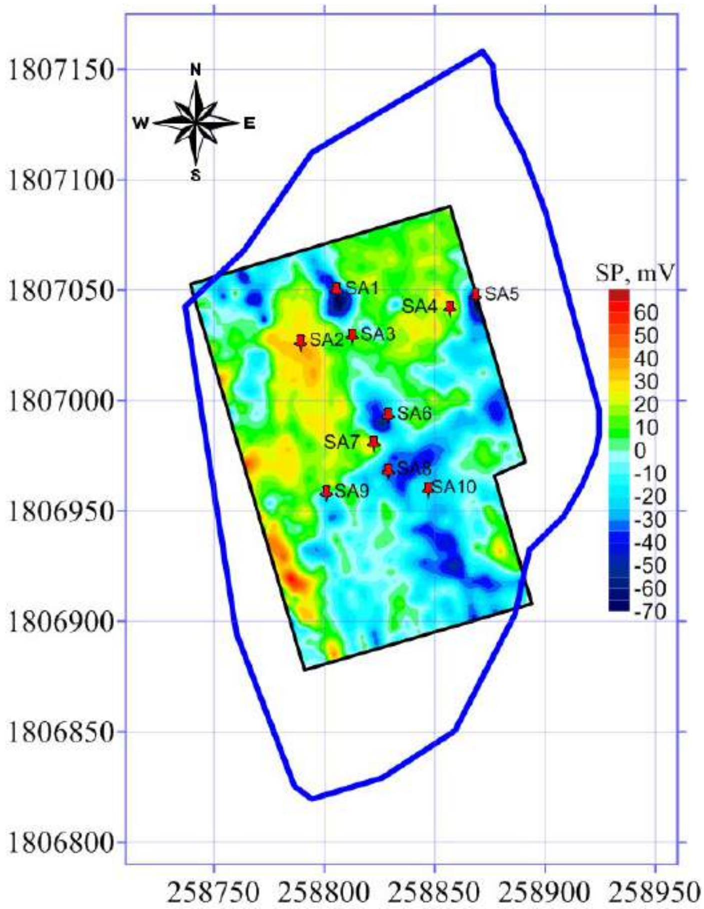


Fig. 11 Locations of auger soundings on the basis of SP mapping results

Descriptions of soil profiles during the auger soundings

Auger Sounding SA 1		
Depth, cm		**Soil Description**
From	**to**	
0	10	Light gray, very sandy, unstructured, dry
10	20	Gray - beige, very sandy, a little more coherent, unstructured, dry
20	50	Humidity increases, clay content increases, increases consistency, light brown
50	120	Small indurated agglomerates waterlogging
120	140	Orange spots, waterlogging clear
140	160	Clayey, plastic
160	200	Very plastic
200	230	Pale gray, color reduction, traces of organic matter
230	270	Grey increasingly pale, very plastic
270 and more		Substratum, sandstone

Auger Sounding SA 2		
Depth, cm		Soil Description
From	to	
0	40	Light gray, very sandy
40	80	Orange, red-ox tracks, very sandy, not coherent, orange
80	120	More clayey, orange
120	150	Clay content increases very linearly, orange
150 et plus		Substratum, sandstone

Auger Sounding SA 3		
Depth, cm		Soil Description
From	to	
0	10	Light gray, very sandy
10	70	Loose sand
70	90	Same wetter
90	110	More clayey, more coherent, visible iron oxide
110	200	Very homogeneous, little trace of iron oxide
200 et plus+		Substratum, sandstone

Auger Sounding SA 4		
Depth, cm		Soil Description
From	from	
0	10	Light gray
10	90	Very sandy very clear, light salmon pink
90	110	Same, but wetter
110	115	Numerous lead shot, rusty colour
115 et plus		Substratum, sandstone, yellow

Auger Sounding SA 5		
Depth, cm		Soil Description
From	to	
0	15	Light gray sandy
15	40	Sandy – clayey, compacted
40	120	Sandy – clayey, color mixing orange spots
120	180	Clayey – sandy, plastic
180	200	Alterite of sandstone, sandy - clayey, lead shot to reduce color (gray)
200 et plus		Substratum, sandstone

Auger Sounding SA 6		
Depth, cm		Soil Description
From	to	
0	15	Very sandy
15	70	Light colored, sandy - clayey
70	100	More orange, more compact, wetter
100	150	Very compact, clayey, manganese oxide stain
150	160	Transition zone to the bedrock, many of lead shot
160 et plus		Substratum, sandstone

Auger Sounding SA 7		
Depth, cm		Soil Description
From	to	
0	15	Sandy, gray
15	50	Sandy, salmon-colored, friable consistency, rather loose
50	90	Consistent with iron oxide, more orange
90	110	Coherent, clayey, iron oxide, wet
110 et plus		Substratum, sandstone

Auger Sounding SA 8		
Depth, cm		Soil Description
From	to	
0	10	Sandy organic
10	30	Beige, sandy
30	90	More and more orange and humid
90	110	Clayey – sandy, gray - beige, progressive change in alterite less clayey
110 et plus		Substratum, sandstone

Auger Sounding SA 9		
Depth, cm		Soil Description
From	to	
0	15	Sand, organic
15	40	Sandy, gray
40	70	Sandy, orange
70	110	More gradual transition to clay concentration of iron oxide
110 et plus		Substratum, sandstone

Auger Sounding SA 10		
Depth, cm		**Soil Description**
From	**to**	
0	15	Sandy organic
15	30	Sandy Gray
30	50	Gray-orange, more coherent, more clayey
50	60	Cohesive clayey
60 et plus		Substratum, sandstone

Descriptions of soil profiles, carried out on the basis of the results obtained during the auger soundings, allowed us to present the initial findings:

- In areas corresponding to positive SP anomalies, the auger soundings (SA 2, SA 3, SA 4, SA 7 in Fig. 11) showed the presence of sandy soils until the depth of 70 – 80 cm. Quite often they are very loose, the cohesion between the grains is nonexistent or very low, and the structure is virtually absent. Clays begin to appear from the depth of 80-90 cm, or only in localized areas, very close to contact with the bedrock substratum. For the sounding SA 7, the soil becomes consistent with iron oxide from the depth of 50-70 cm and clays appear from 90 cm deep.
- In areas where are observed highly localized SP negative anomalies, the clays are appeared from the depth of 15-20 cm (SA 1, SA 5 and SA 6). For the soundings SA 8 and SA 9, which are located on the plot of Pueraria, soils are sandy, sandy - loamy until the depth of 70-90 cm, like in the areas with positive SP anomalies. Obviously, the SP negative anomalies are generated by a high concentration of nitric ions (anions NO_3^-), resulting the effect of agronomic experimentation, i.e., the nitrogen enrichment of soil.
- For the SA 10 sounding, where the zone is characterized by moderate negative anomaly, the roof of the bedrock is located at 60 cm depth and clay content becomes perceptible from 30 cm deep.

B. Results of apparent electric resistivity mapping

The superficial horizons of sandy and sandy - loamy soils, covering a large part of this site, are characterized by their light texture and low capacity of water retention. We have noticed this fact for a similar prospecting, which we would like realize in November 2009, just after rainy season. During this period, the inappropriate conditions with very high resistance of contacts between electrodes and ground, have not allowed us to perform properly measurements and achieve this prospecting.

In 2010, we began apparent electric resistivity mapping of "Ban Non Tun" site on October 13, before the end of the rainy season. The soil was moist enough until the end of mapping works (November 17), which provided good conditions for galvanic contacts between the electrodes and soil. The daily rainfall data corresponding to the period of this geophysical prospecting are presented on Fig. 12.

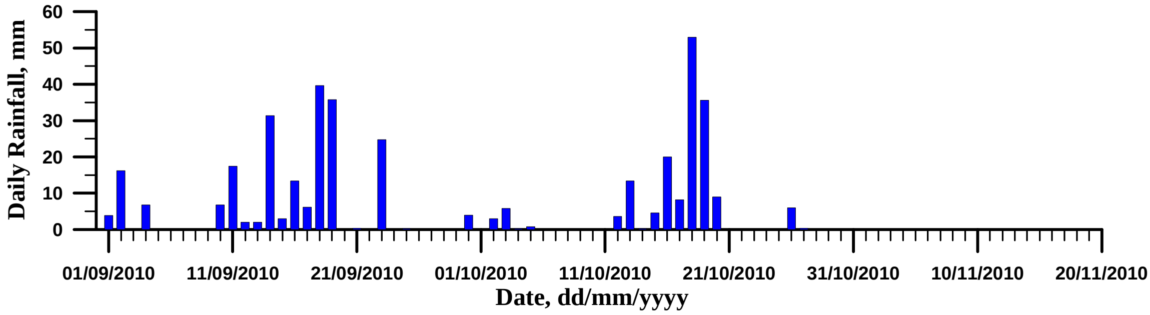


Fig. 12 Daily rainfall registered on "Ban Non Tun" site from September 1 to November 20, 2010

We started work from the southern part of the experimental site, which one topographically corresponds to the "up-slope" area. In this area, the soils are characterized by their small thickness (only 40-60 cm), coarse grain size and low capacities of the water retention. So, the risk was higher to not be able to ensure the measurements of good quality in this zone after the rains stopping, relative to the zones of "middle-slope" and "low-slope" of the site. On the Fig. 13 are shown the daily mapped plots in scale of the site, that we did effected according to the weather (rain) or field conditions (flooding).

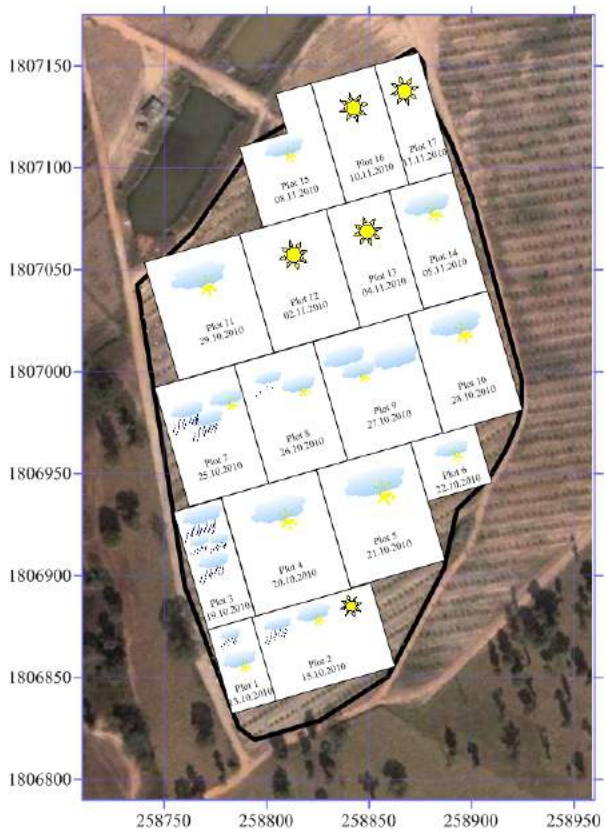
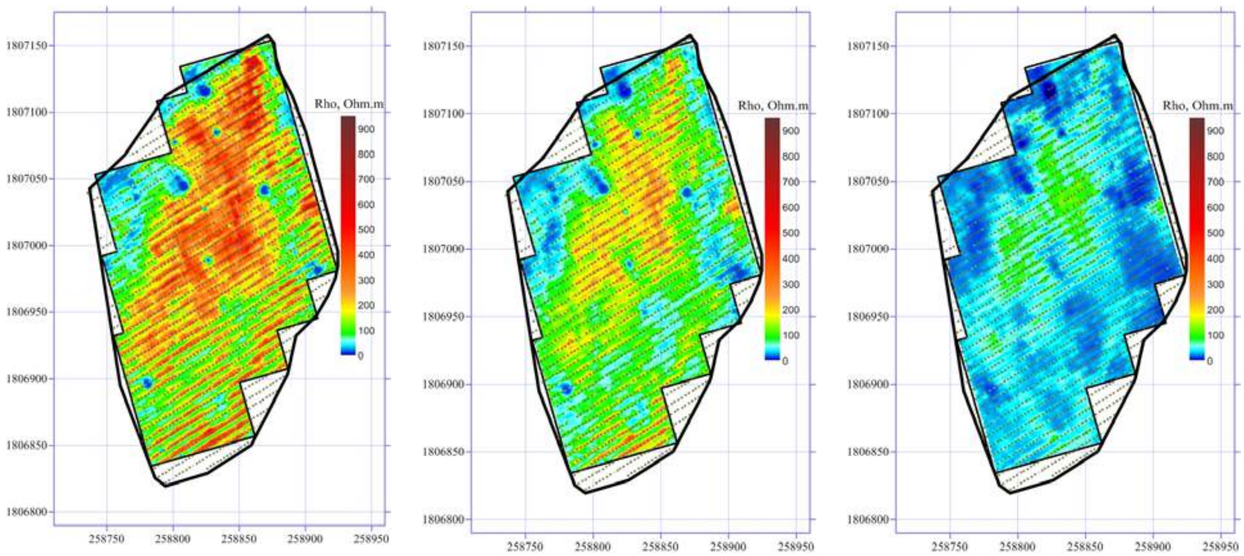


Fig. 13 Dates, daily mapped plots and weather conditions during electrical resistivity mapping (in UTM system of coordinates)

Changing weather conditions, especially the sequences of the rain and sun, had affected the level of water content in the soil, and therefore, the measured apparent electrical resistivity values had changed also. A specific approach of data processing was used for correcting the results, in order to bring them to the same level corresponding to the weather conditions at the beginning of the mapping.

The mapped zone has a surface of 3.6 ha and covers more than 95% of the surface area of the experimental site (Fig. 13). In total, about 150 000 measurements of apparent electrical resistivity were performed to realize the maps corresponding to three different depths (Fig. 14).



a. a = 0.5 m **b.** a = 1.0 m **c.** a = 2.0 m

Fig. 14 Apparent electric resistivity maps (in UTM coordinate system) with different spacing between mobile electrodes C1 and P1: i. a = 0.5 m, ii. a = 1.0 m and iii. a = 2.0 m (Gray points correspond to the positions of trees)

The mapping results of the site "Ban Non Tun" showed spatial variability of apparent electrical resistivity (ρ_a) in a wide range: from 10-15 Ohm·m to 800-900 Ohm·m. We can consider that this variability is caused by the difference of soil characteristics, and represents, in some way, the spatial variability of soils. With depth, the apparent electric resistivity values decreased, and the results have become less contrasted (Fig. 14). In the central part of the planting, soils are characterized by relatively high values of ρ_a, from 500 to 900 Ω·m. This area is surrounded by variable width stripes, where values of apparent electrical resistivity vary between 50 and 150 Ω·m. The conductive anomalies ($\rho_a < 50$ Ω·m) have very localized forms and may be distinguished in various parts of this experimental planting.

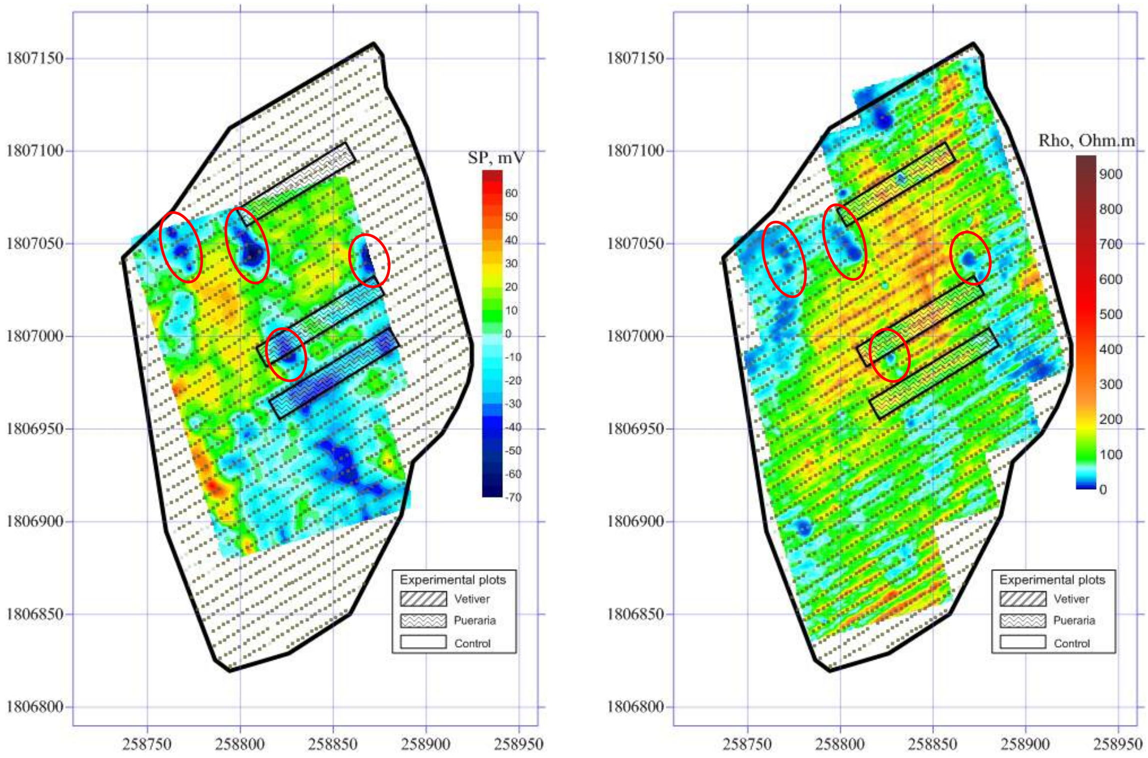
However, the most conspicuous feature of this map is the presence of strong resistive anomalies extended along the tree ranks (Fig. 14 a & b). Since the apparent electrical resistivity mapping were carried out following profiles oriented at 75° relative to the direction of tree ranks, these anomalies cannot be due to herringbone effects or other artefacts.

The results of several studies indicates that the roots of trees or other plants (called underground biomass) can lead to resistive anomalies during electrical resistivity prospecting (Amato *et al.*, 2008, Rossi *et al.*, 2011). In these studies, the ground surface is presented as flat, and, unfortunately the authors are not considered the influence of topography on the electrical resistivity measurements before interpreting geophysical data. Following this analysis, it is not possible to directly link these anomalies with root system's functioning of trees, because the differences in altitude between the "ranks" and "inter-rank" areas can affect the electrical resistivity measurements and generate apparent electrical resistivity anomalies (called "topographic effect").

To understand the nature of these anomalies and to estimate the contributions of various sources, I proposed an additional NRCT project for the internship of a Master 2 degree French student (Mr.Sylvain Pasquet) in Applied Geophysics, which I supervised with my colleagues from LDD (Khun Nopmanee Suvannang and Dr. Rungsun Imerb). Detailed analysis of the geophysical prospecting results and numerical modeling, performed during this project, allowed us to estimate the impact of the "topographic effect" on the measured values of apparent electrical resistivity and has shown that these extended resistant anomalies can be primarily related to the land management works. Elevated parts of the relief, corresponding to the "tree ranks", were created by extracting the soil in the "inter-rank" areas to transfer it on the ranks of trees. These works certainly lead to a significant degradation of the soil structure which can explain the increase of their electrical resistivity. (Pasquet, 2011).

Discussion and analysis of results

The maps of the experimental site "Ban Non Tun", obtained by various geophysical methods, were used to jointly analyze the behaviours of different physical parameters and have contributed to understand their variations linked with the changes of soil characteristics. The comparison of geophysical mapping results reveals clear coherence between the SP anomalies and the observed values of apparent electrical resistivity (Fig. 15 a & b). One can easily notice that the negative, strong and highly localized anomalies (-50 - -70 mV) of the spontaneous potential correspond to the conductive anomalies (around 20 Ohm.m) on the apparent electrical resistivity map (marked by ellipses). The observation of negative SP anomalies and low resistivity values at the same locations can be explained by the presence of wet clays in the soil. Usually, the clayey particles are charged negatively at their surface, and may be the source of negative electrical potential. Clays are characterized also by their very high capacity for water retention. The water in the soil, is naturally charged of ions and may generate a higher electrical conductivity (or lower resistivity), compared to the surrounding medium (sand or sandstone). This assumption was validated by the results of several auger soundings, confirming the existence of clay in the part near the ground surface (15 to 30 cm deep). In other places, clays appear only in the deeper layers, closer to the weathered zone of bedrock.

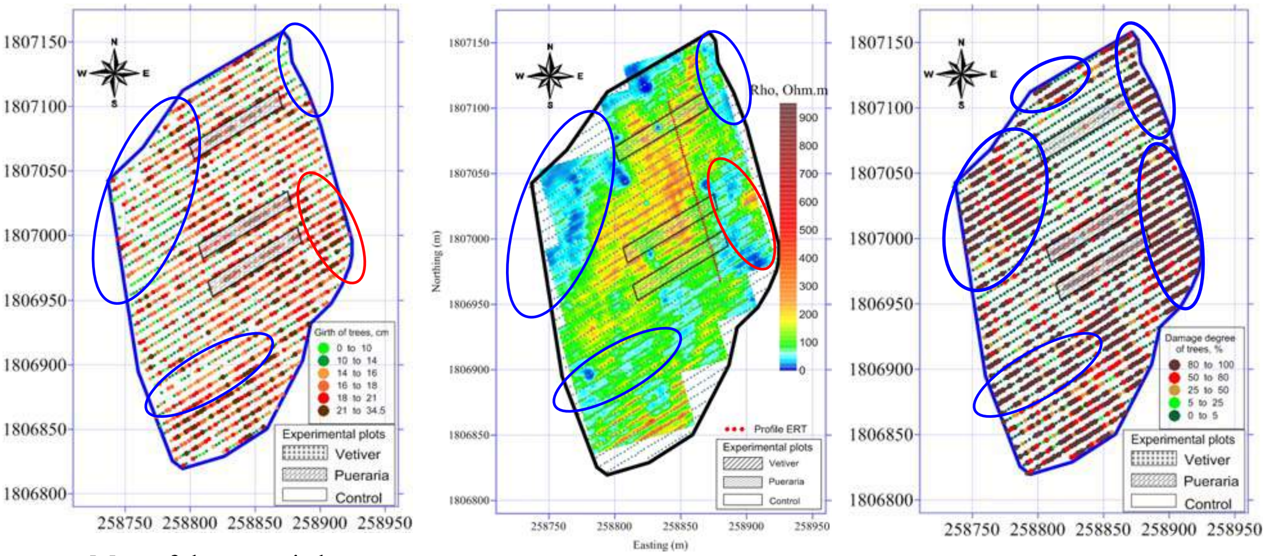


a. b.

Fig. 15 Comparison of SP (a) and of apparent electric resistivity (a=1.0m) prospecting results (b)

Negative anomaly on the farther south plot of ***pueraria*** (Fig. 15 a) could correspond to a high concentration of fixed nitric (NO_3^-) ions, resulting from the agronomic experimental procedures. It is known, that nitrogen in soil is present in various chemical forms and undergoes permanently modifications, due to of biogeochemical transformations and under the influence of different interactions with atmospheric oxygen and with water containing in the pores. The forms ammonia (NH_3) and ammonium (NH_4^+) of the nitrogen are not stable and their concentrations in the soil cannot be high. In soils, nitrogen is very often present as nitric (NO_3^-) ion, and it is logic to assume a higher concentration of this ion in the ***pueraria*** plot, implemented especially, to enrich the soil by nitrogen. The fact, that a high concentration of nitric (NO_3^-) ions in this plot of ***pueraria*** does not generate a conductive anomaly can be explained by the light texture and relatively coarse-grained soils in this area, by their low capacity of water retention and by reduced mobility of NO_3^- ions.

The results of chemical analysis and the observations of the tree growth also show a relatively high nitrogen content in the plots of ***pueraria*** compared to other areas of the site (Pongwichian et al., 2010). On the map (Fig. 16 a) representing the girths of trees, measured in September 2009 (after around 3 years of their plantation) at the height of 140 cm from the ground, it is easy to distinguish, that in the plots of ***pueraria*** the trees are characterized by large circumferences. The relatively high growth of trees in these plots is certainly linked to the high concentration of nitrogen in the soil, as a result of agronomic experimentation. It should be noted, that the trees with roughly the same growth, we can find in other parts of the planting, far from pueraria plots, e.g., in the southern part of the site (Fig. 16a).



a. Map of the tree girths

b. Map of apparent electrical resistivity: a = 1.0 m

c. Map of the tree states evaluation

Fig. 16 Comparison of the agronomic observation results (c & c) with the apparent electrical resistivity mapping (b) (Points correspond to the positions of trees)

The comparison of the results of tree growths (Fig. 16a) with the map of apparent resistivity (Fig. 16b) reveals a general trend: areas with slow growing trees (marked by blue ellipses) correspond to zones with low values of apparent electrical resistivity. There are, of course, some exceptions, when this trend is reversed, for example, in the eastern part of planting, where the larger trees are placed in a conductive zone (marked by a red ellipse). A detailed study of this area had been expected in order to understand this functional difference, but could not be performed because of my return to France, and then by the change of culture (in 2012 the rubber tree planting was replaced by eucalyptus).

The natural growth of rubber trees was affected by a water stress due to the long period without major rain events between October 2009 and June 2010 (Fig. 17). While in 2007 the rainfall was close to the annual average (about 1300 mm), typical for this region, the year 2008 was characterized by heavy rainfall (over 1900 mm), followed by an important deficit of rains in 2009 (only 1170 mm) and in 2010 (1165 mm). These extreme weather conditions have significantly damage the trees in this plantation, resulting in their partial or complete drying.

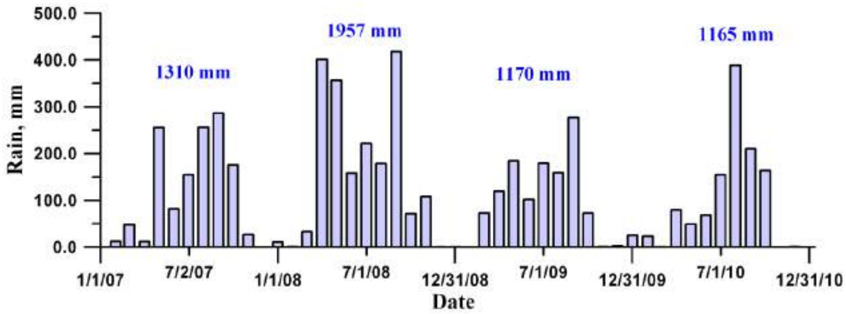


Fig. 16 Rainfall in experimental site "Ban Non Tun" between 2007 and 2010

In 2010, the rainy season was delayed more than one month compared to previous years. After a relatively long period without rain, from mid-October 2009 until the end of April 2010, the lack of humidity and the high intensity of evapo-transpiration, due to exceptionally high temperatures, have created unsuitable conditions for rubber trees. A survey of the states of trees in this planting, carried out in July 2010, revealed that many of trees have suffered, and part of them was completely dried. During this observation, we examined the states of each tree to assess the total damage to the plantation. To present these results in a map form, we have classified the states of trees as follows:

- trees completely dry - 100% damaged;
- trees with branches at the top completely dry, but with new branches growing on the trunk in its lower part, we evaluated - 80% damaged;
- trees on which some branches were dry and the rest were in normal states, we calculated the number of dryed branches to the total number of branches as a percentage;
- trees in normal state - 0%.

The results of this investigation have shown that more than 40% of the trees were damaged over 80%, i.e. irreversibly, and, about 40% of them survived (damaged less than 5%) under the conditions of hydric stress (Fig. 16 c). Comparing these results with the apparent electrical resistivity map (Fig. 16 b) highlights the locations with highly damaged trees (marked by blue ellipses on Fig.16c) correspond to areas with small values of apparent electric resistivity. When the water content decreases in the soil, the roots of trees have problems getting the necessary amount of moisture in areas where the content of fine particles in soil is high. These soils are characterized by high capacity of water retention which may disrupt the normal functioning of tree roots. These results also show that the damage of trees is important in areas characterized by relatively high growth, especially in the southern part of the plantation (Fig. 16 a), where the thickness of the soil is quite low. The roots of great trees require higher amount of moisture which is not possible under these conditions.

On the map representing the results of damaged trees (Fig. 16 c) we can notice the large number of dry trees on the plots of ***pueraria*** placed in the "up-slope" and "middle slope" of the site. This may be the result of a tough competition between the roots of ***pueraria*** and rubber trees under conditions of very low humidity in the not deep soil. (Fig. 17).

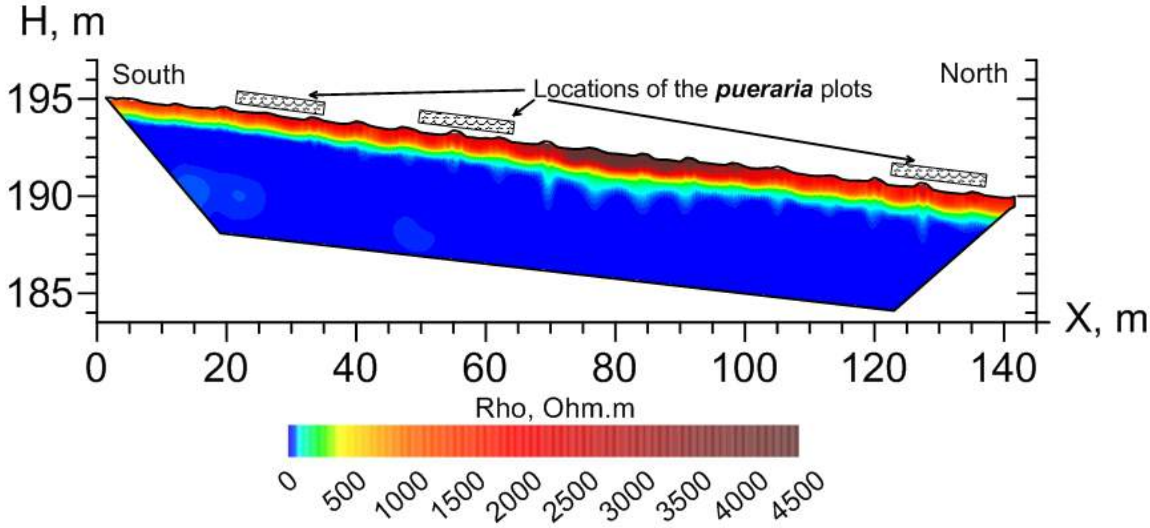


Fig. 17 Electrical resistivity model obtained by 2D ERT on the site Ban Non Tun in the direction approximately South-North

In fact, 2 dimensional electrical resistivity tomography (2D ERT) (Fig.17) revealed a greater thickness of soil corresponding to the plot, located in the North of the site. Very likely, the location of this plot in downstream of the site is causing more favorable conditions (humidity, soil thickness and texture) to the growth of rubber trees, which also explains the higher resistance of the trees against hydric stress.

Coherence between the results of the geophysical prospecting, of auger soundings and agronomic observations indicates the high performance of the apparent electrical resistivity mapping to study the soil spatial variability.

Conclusions and Recommendations

1. Analysis of the geophysical prospecting results, obtained by using different methods and parameter, allowed understanding the nature of the observed anomalies and to link them with the physical characteristics of soils that may explain the spatial variability of soils.

2. The coherence of the results of geophysical prospecting and of agronomic observations, like the similarity between the contour shapes on the maps of geophysical parameters and agronomic variables, demonstrate the influence of the soil spatial variability on plant functioning and, particularly on their growth and behavior under extreme hydrological conditions. At the same time we also observed the fact of the agronomic experimentation influence on soil physical and chemical characteristics.

3. The results obtained during this project showed the sensitivity of geophysical parameters relative to the soil properties (inorganic part) and to the "soil-plant-atmosphere" interaction processes, where the participation of the nutrients and of the micro-organisms becomes very important (organic part). The results show the usefulness of geophysical surveys to study and understand the phenomena that occur at different levels of interaction "soil-water-plant-atmosphere".

The results of this work have shown the effectiveness of geophysical surveys for studying the spatial variability of soil, and also, that this variability may be very important at the scale of a planting. The high gradients of different characteristics of the ground can significantly influence not only on the process occurring between the various components and compartments of the soil, but also to change the conditions of interaction between soil and plant. To study in detail the interactions "soil-water-plant-atmosphere" and assess the resources of water and soil, to ensure normal growth of the chosen plant or crop, it is always necessary to organize specific laboratory or field experiences under controlled conditions.

It would be preferable to conduct geophysical exploration before beginning field experiments in order to study the initial conditions and baseline characteristics of soils.

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ANNEX

Summary of Results for the symposium GEOFCAN - GFHN in France

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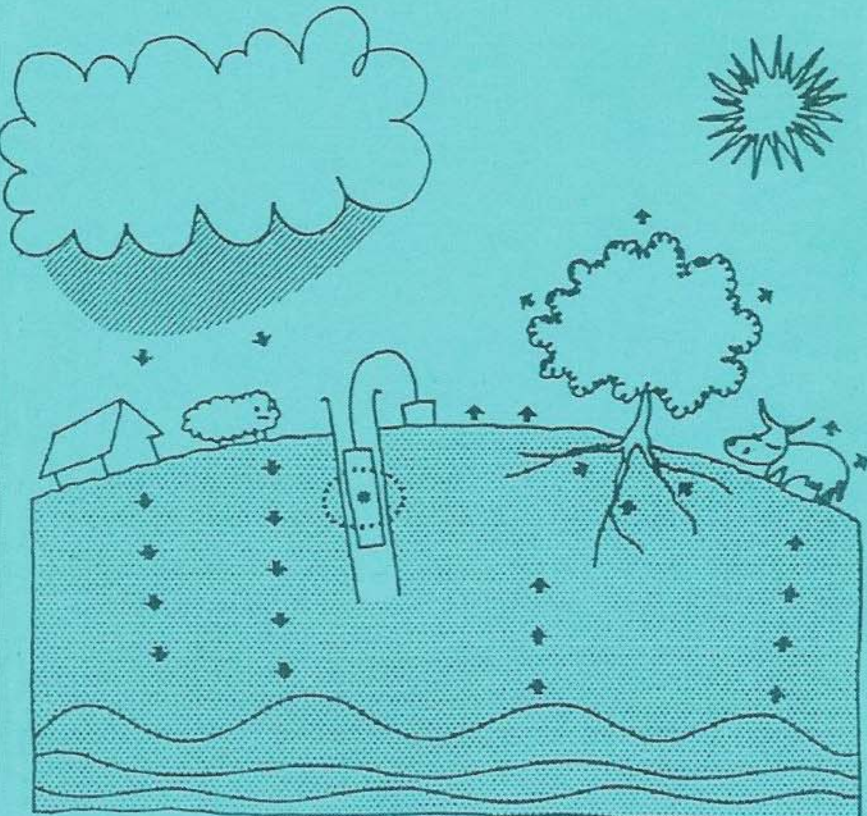
MILIEUX POREUX ET TRANSFERTS HYDRIQUES

BULLETIN DU GROUPE FRANCOPHONE HUMIDIMÉTRIE ET TRANSFERTS EN MILIEUX POREUX



N° 57

ÉTUDE DE LA VARIABILITÉ SPATIALE DES SOLS ET DES PROCESSUS D'INTERACTION « SOL-EAU-PLANTE-ATMOSPHÈRE » PAR DES MÉTHODES GÉOPHYSIQUES DANS DES PLANTATIONS D'HÉVÉA EN THAÏLANDE

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RÉSUMÉ

Les résultats de cartographies de potentiel spontané et de résistivité électrique apparente montrent des cohérences fortes entre les paramètres géophysiques, les caractéristiques des sols et les observations agronomiques. L'application des méthodes géophysiques permet de mieux comprendre les processus d'interactions « sol-eau-plante-atmosphère » et d'étudier l'influence des caractéristiques des sols sur le fonctionnement des plantes dans des conditions spécifiques.

Mots clés : plantation d'hévéa, cartographie géophysique, variabilité spatiale des sols, usage des terres, caractéristiques des sols, stress hydrique.

ABSTRACT

STUDY OF SOIL SPATIAL VARIABILITY AND INTERACTION PROCESS "SOIL-WATER-PLANT-ATMOSPHERE" BY GEOPHYSICAL METHODS IN RUBBER TREE PLANTATIONS OF THAILAND

The results of the mapping of spontaneous potential and apparent resistivity show a strong consistency between geophysical parameters, soil characteristics and agronomic observations. Application of geophysical methods allows to better understand the processes of interaction "soil-water-plant-atmosphere" and to study the influence of soil characteristics on the behavior of plants under specific conditions.

Key words: rubber-tree plantation, geophysical mapping, spatial variability of soils, land use, soil characteristics, water stress.

1. INTRODUCTION

La production de caoutchouc naturel est devenue un atout économique important pour la Thaïlande, car elle est le premier pays au monde de production et d'exportation de ce produit. La demande de caoutchouc naturel sur le marché international est en hausse, le prix est élevé. En plus de ces derniers, les subventions du gouvernement thaïlandais ont créé des conditions favorables pour l'expansion des plantations de l'arbre à caoutchouc (hévéa), même dans les zones considérées marginales par rapport à son biotope originel.

La région de Khon Kaen (au Nord-Est de la Thaïlande), où se trouve le site expérimental de Ban Non Tun, est caractérisée par un climat semi-aride tropical dominé par la mousson (WATANABE et al. 2004). Les précipitations totales restent inférieures à l'humidité nécessaire pour l'arbre hévéa et leur distribution est irrégulière.

Dans cette région, où les sols sableux ne sont pas riches en matières organiques et autres nutriments, il est très important d'appliquer une stratégie de la gestion des terres qui permette, d'une part, de réhabiliter les sols et les préserver contre l'érosion et la dégradation, et d'autre part, d'assurer un bon rendement et garantir les revenus dans des exploitations de petite taille. Une expérimentation agronomique est en cours ; elle a pour but de protéger le sol contre l'érosion par une couverture végétale et d'enrichir le sol en l'azote (parcelles de pueraria) en utilisant les espaces entre les rangs des jeunes arbres, avant qu'ils deviennent exploitables.

Le sol est un milieu naturel résultant de l'interaction entre différents facteurs, comme la composition de la roche mère, le climat, la topographie, le fonctionnement hydrique, l'activité biologique, le temps, etc... Les variations de la nature et de l'intensité de la plupart des processus impliqués dans la pédogenèse aboutissent à des hétérogénéités et des discontinuités de la couverture pédologique. Cette variabilité, aussi bien verticale que latérale, peut être révélée et étudiée en utilisant différentes méthodes de la Géophysique appliquée (TABBAGH et al. 2000).

2. ANALYSE DES RÉSULTATS OBTENUS

Pour étudier la variabilité spatiale des sols de ce site et son influence sur les interactions « sol-eau-plante-atmosphère », les cartographies de potentiel spontané (PS) et de résistivité électrique apparente (ρa) ont été réalisées (**cf. Fig. 1**). La comparaison de ces cartes met en évidence une cohérence entre les anomalies PS fortement négatives (de -50 à -70 mV) et très localisées et les anomalies conductrices, avec ρa de l'ordre de 20 Ω·m. L'observation aux mêmes endroits de ces anomalies peut être expliquée par la présence d'argiles dans le sol. Celles-ci sont chargées négativement à leur surface et peuvent être à l'origine du potentiel électrique négatif mesuré par la méthode PS. Les argiles sont également connues pour leur forte capacité de rétention d'eau. Cette eau, présente dans le sol, est naturellement chargée en ions et peut générer une conductivité électrique plus élevée par rapport au milieu environnant (grès, sable,...).

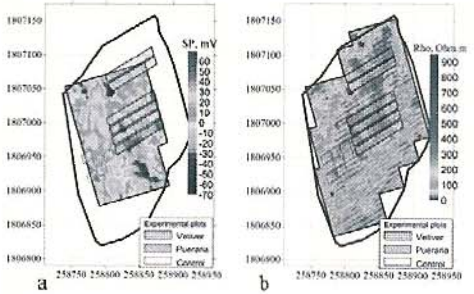

Fig. 1 - Cartes de potentiel spontané (a.) et de résistivité électrique apparente pour a = 0.5 m (b.) du site de Ban Non Tun

Les résultats de sondages à la tarière aux emplacements de ces anomalies confirment la présence d'argile dans la partie superficielle du sol (15 - 30cm de profondeur). Dans d'autres endroits, les argiles apparaissent dans les couches plus profondes (70-90cm) et proches de la zone d'altération de substratum.

Les résultats obtenus montrent une tendance générale où la croissance des arbres est faible dans les zones moins résistantes (**cf. Fig. 2 a et b**). Seule une croissance relativement élevée des arbres plantés sur une zone conductrice située à l'Est du site (ellipse rouge) contredit cette tendance. Une étude détaillée est prévue dans cette zone pour comprendre cette différence de fonctionnement.

Les hévéas plantés dans les parcelles de pueraria sont majoritairement caractérisés par des grands diamètres (**cf. Fig. 2b**). Cette croissance relativement élevée est probablement liée à la forte concentration d'azote dans le sol, suite à l'expérimentation agronomique.

La croissance naturelle des arbres a été perturbée par un stress hydrique suite à une longue période de sécheresse entre octobre 2009 et juin 2010.

En juillet 2010, une observation de l'état de chaque arbre a été réalisée pour évaluer leur endommagement. Le degré d'endommagement des arbres a été défini par le rapport entre le nombre de branches sèches et le nombre total de branches (arbres non-détériorés – 0 % et arbres complètement secs – 100 %).

Une comparaison des résultats de cette observation (**cf. Fig. 2c**) avec la carte de résistivité électrique apparente (**cf. Fig. 2a**) montre que les arbres fortement endommagés sont localisés dans les zones moins résistantes, ainsi que dans les deux parcelles de pueraria situées plus au Sud.

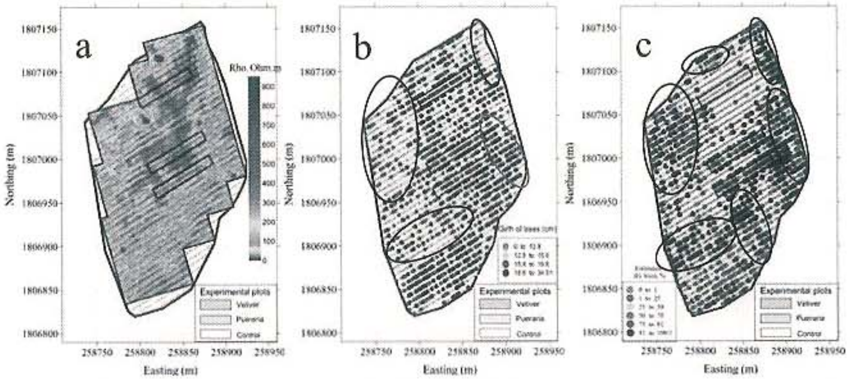

Fig. 2 - Comparaison de la carte de résistivité électrique apparente (a.) avec les résultats des observations agronomiques : circonférence (b.) et état des arbres (c.)

Du point de vue de l'interaction entre la plante et le sol avec une faible humidité, le fonctionnement normal des racines des arbres peut être perturbé par l'influence de la forte capacité de rétention d'eau des argiles. Le nombre considérable d'arbres endommagés sur les parcelles de pueraria est certainement le résultat d'une compétition forte entre les racines des deux plantes dans des conditions de faible humidité et d'épaisseur limitée du sol. Une tomographie de résistivité électrique révèle que l'épaisseur de sol est plus importante dans la parcelle de pueraria, située au Nord du site. Sa position en aval avec des conditions (hydriques, épaisseur et texture des sols) plus favorables à la croissance des hévéas expliquerait aussi la meilleure résistance des arbres dans cet emplacement face au stress hydrique.

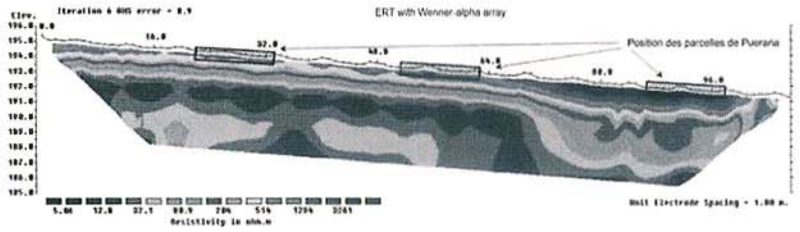

Fig. 3 – Distribution de la carte de résistivité électrique obtenu par ERT sur le site de Ban Non Tun dans la direction Sud-Nord

Les cohérences entre les observations agronomiques, les prospections pédologiques et les variations spatiales des paramètres géophysiques (PS, résistivité électrique apparente) montrent l'intérêt des études inter-disciplinaires.

3. CONCLUSIONS

Les résultats obtenus mettent en évidence la sensibilité et l'efficacité des paramètres géophysiques dans l'étude des interactions « sol-eau-plante-atmosphère ».
La cohérence entre les résultats de prospections géophysiques et les observations agronomiques montre l'influence de la variabilité spatiale des sols sur la croissance et le fonctionnement des systèmes racinaires des plantes. En même temps, ces résultats révèlent aussi l'impact de l'expérimentation agronomique sur les caractéristiques des sols.

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