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Can organic management enhance biology and alleviate the soil compaction problem in Thailand ? A study of soil physical and biological parameters

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Diplôme : Master en bioingénieur : sciences et technologies de l'environnement, à finalité spécialisée
Année académique : 2022-2023
URI/URL : http://hdl.handle.net/2268.2/18135

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A STUDY OF PHYSICAL AND BIOLOGICAL SOIL PARAMETERS

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This work was carried out in collaboration with the Soil Physics laboratory of the Agricultural Development Research Center in Northeast Thailand and Department of Soil Science and Environment of the Faculty of Agriculture in Khon Kaen University and the Water-Soil-Plant Exchanges axis of the Faculty of Gembloux Agro-Bio Tech, Liège University. The student was funded by the Erasmus+ program.

Acknowledgements

First of all, I would to thank the people of the Faculty of Agriculture in KKU and the Research center for the warm welcome and the allocation of laboratory equipment, even with the language barrier you helped me carry out my experiments in the best conditions. To the people that made the exchange wonderful, thank you very much. You made my exchange in Thailand unforgettable.

Thank you Ajarn Chuelmas for all the wonderful travels in East Asia and the valuable insight on the research world. Thank you for your support and your kindness.

Thank you the Chuleemas Gang for the shared experience, the help, the support and the fun moment. I would like to thank especially P’Zom, P’Jo, P’Ket, Fly for the help on the field sampling, Preaw and Fly for the collaboration on the experiment and the research. Thank you Baitong for your wonderful help through the numerous Thai organisations, the interview of the farmer as well as your valuable insight on Thai agricultural system. Thank you Pare for the help and the drives from the dorms.

Thank P’Ayco and P’Ploy for the adventure days. And lastly, thank you Seki for being a wonderful friend and making me discover the student life in Thailand.

Ensuite, je voudrais remercier ma promotrice, Pr Aurore Degré pour sa confiance et cette magnifique opportunité. Un grand merci également pour votre disponibilité, vos encouragements. Ce fut un plaisir de travailler avec vous.

Merci également aux occupants de l’axe et du Topo, vous m’avez partagé de bons petits tips et rendu les longues journées plus agréables.

Merci à tous les copains qui m’ont soutenu pendant cette épreuve finale. Merci Anne-K pour ton soutien à distance et de m’avoir rassuré à chaque moment de panique. Merci Liso, Marga et Lulu pour les longues journées (et nuits) partagées dans l’Hydrotech. Votre soutien et nos interactions m’ont permis de développer mon TFE.

Merci à toutes les personnes que j’ai rencontrées au fil de mes études, vous avez rendu ces années estudiantines inoubliables. Merci au kot Mijolles et à Cam’s pour toutes ses soirées de folie, ces fritures, ces moments de partage dans les canaps.

Finalement, un grand merci à ma famille pour son soutien constant durant mes études et encore plus présent pendant ces derniers mois.

Abstract

Soil degradation becomes an pressing issue to ensure food supply for the growing population. Soil compaction reduces soil quality through change in several soil parameters. The aim of this study is to assess the influence of compaction on soil parameter on two depths. This influence was studied on several land-use and agricultural practices in Northeast Thailand. Conventional sugar cane, paddy rice, cassava, organic cassava and forest are the land-uses observed. The analysis concerns soil hydrophysical and biological parameters and their interaction. The studied hydrophysical parameters are bulk density, soil water retention curve using pression plates apparatus and psychrometer, pore size distribution and hydraulic conductivity. The biological parameters are assessed through casts and earthworms density as well as soil respiration. Results displays high bulk densities, especially in the subsoil. Impact of management practices is displayed on water characteristics and on the biological parameters. However, the highlighted relations between parameters nuance literature and enhance the need for global approaches of soil quality. Further studies are required to quantify the impact of sustainable management practices on soil and the implementations of such practices in the tropical context.

Résumé

La dégradation des sols et le maintien de la santé des sols devient un problème urgent afin d'assurer la sécurité alimentaire pour la population mondiale en continuelle expansion. La compaction des sols est un processus de dégradation qui réduit la qualité du sol en affectant ses propriétés. Le but de cette thèse est d'étudier l'influence de la compaction sur les paramètres hydrophysiques et biologiques des sols à deux profondeurs. Cette influence a été quantifiée pour plusieurs cultures et pratiques agricoles dans le contexte du Nord-Est de la Thaïlande. Des cultures conventionnelles de canne à sucre, riz et manioc ainsi qu'une culture de manioc avec fertilisation organique et une forêt ont été étudiées. Les paramètres hydrophysiques analysés sont la densité apparente, la courbe de rétention en eau déterminée avec des plaques de pression et un psychromètre, la distribution de taille des pores ainsi que la conductivité hydraulique. Les facteurs biologiques étudiés sont la densité de vers de terre et de leurs déjections ainsi que la respiration du sol. Les résultats démontrent d'importantes densités apparentes, surtout dans le sous-sol. L'impact des pratiques agricoles sur les paramètres hydriques et biologiques est constaté. Les relations mises en lumière lors de l'analyse contrastent la littérature et mettent en avant la nécessité d'approches globales de la qualité des sols. Des études supplémentaires sur l'implémentation de pratiques agroécologiques et leur impact en contexte tropical sont nécessaires afin de garantir une agriculture durable et le maintien de la santé des sols.

Table of contents

List of tables

List of figures

I. Introduction

Soil compaction

As soil is a non-renewable resource, sustainable use of it and its ecosystem services is necessary in order to deal with the food supply and the increasing demand as the population is growing (Nawaz et al., 2013) especially, since soil degradation is as old as agriculture. Restoring soil in order to have healthy soil to grow crops is a current challenge of this time (FAO, 2020). Soil health defines as "the ability of the soil to sustain the productivity, diversity and environmental services of terrestrial ecosystems" by the Intergovernmental Technical Panel on Soils (ITPS) (FAO, 2021). Intensification of land use and other human-induced changes can modify soil structure and biotic and abiotic properties and thus influence ecosystem services delivery (FAO, 2021).

One of the issues of soil degradation is compaction which happens under various soil types and climates. It’s estimated that 68 millions ha worldwide are affected by soil compaction with tillage (Nawaz et al., 2013). Compaction is defined, in *The Glossary of Soil Science Terms*, as “the increasing of the soil bulk density, and concomitantly decreasing the soil porosity, by the application of mechanical forces to the soil”. It happens on the surface of the land, within the tilled layer or at greater depth with a thickness varying from a few millimetres up to 20-100 mm (Batey, 2009; Hamza & Anderson, 2005). The physical changes induced by soil compaction cause a hidden degradation of the soil, difficult to locate because there is no visual effect on the soil surface unlike soil erosion or salinity (Hamza & Anderson, 2005; Nawaz et al., 2013).

Soil compaction changes the soil productivity. Batey (2009) said that "The compaction of soil affects adversely nearly all properties and functions of the soil, physical, chemical and biological". Indeed, surface and subsurface compaction induce soil erosion, runoff and nutrient depletion. It has therefore effects on crop growth, yield and quality by reduction of the root depth and nutrient uptake and/or formation of waterlogged or anoxic zones. In compacted soil, roots are mostly in the macropores and thus extract water and nutrients at a slower rate. As compaction can reduce the roots' foraging ability, the plants are less capable to respond to the transpiration demand. Therefore warmer and drier climate may a have a severe effect on crop production because roots are unable to reach the water in the subsoil. For farmers, the main consequence is a variation in the growth of high-values crops with a proportion of the crop of lower value or sometimes, unmarketable (Batey, 2009). Various activities may cause compaction such as agriculture, forest harvesting, amenity land use, pipeline installation, land restoration and wildlife pathways. Soil compaction also occurs with natural phenomena such as rain, plant roots growth but with a lower impact. The sensitivity to compaction influences the workability and trafficability of the soil which depends on the interaction between climate and soil physical properties (Batey, 2009).

Soil compaction factors

The compaction degree of soils depends on a wide range of factors such as the loading, the characteristics of the wheels of the tractor, the water status of the tilled layer, its structure, and the soil mechanical strength which is influenced by soil texture and organic matter content (Hamza & Anderson, 2005). Compressive forces applied on a compressible soil cause soil compaction. Those forces can come from wheels under tractors, trailers, harvesters but also

from pressure under the hooves of grazing animals (Batey, 2009; Bluett et al., 2019; Hamza & Anderson, 2005; Nawaz et al., 2013).
The wheels of farm machinery compact the soil and decrease soil porosity localised in the zone beneath the wheel. Overcompacted soils are found mostly along the wheel tracks and the turning strips at field edges. It is the inflation pressure that affects the topsoil while the axle load affects the subsoil. Important factors of the wheels are the wheel load, the type of tyre and the inflation pressure. Only certain types of tyres increased soil compaction near the track. At greater distances of the track, the compaction generally decreases, especially in the subsoil. Some farmers noticed that by working with low pressure tyre, the soil compaction can be reduced and the crop yield increased. The number of passes is an important element in soil deformation. It has been showed that all soil parameters become less advantageous for agriculture after one passage. After ten passes, the advantage of a light tractor to heavier machinery is lost. Therefore, agricultural machines that do several operations at the same time protect soil by decreasing the number of wheel passes. In order to have a soil with adequate physical properties, farmers claim conventional or minimum tillage is better than no-tillage as critical values for severely restricted root penetration were observed in no-tillage system. However, recent studies show that, in time, yield in no-tillage system exceed the other tillage management (Godwin et al., 2022). The suitability for long-term no tillage depends on the soil's susceptibility to compaction. The resistance to compaction relies on several properties : structural stability of the topsoil, which comes from great organic matter content but also calcium carbonate and good drainage (Batey, 2009; Hamza & Anderson, 2005).

Indeed, another major factor of soil compaction is the water content (Nawaz et al., 2013). Water content represents the quantity of water in the soil (Kirkham, 2014a). The compaction process is increased when the soil is worked under high soil water content. The depth to which the compaction is transmitted depends on the moisture profile of the plot. A field worked under high moisture content has a reduced load capacity of the soil thus the permissible pressure is decreased whereas at low water content, even maximum loads do not deform the soil more than two centimetres deep (Hamza & Anderson, 2005). Usually, good working conditions are generated with a soil moisture content lower than field capacity. Therefore, drainage capacity and climatic conditions impact the process of compaction and poorly drained soils are more at risk (Batey, 2009).

Another impact comes from the soil texture which is the relative percentage of sand, silt and clay fraction in the soil (Indoria et al., 2020). The workability decreases as the clay content increases. Furthermore, coarse sandy soil can be worked under a wide range of moisture contents but they can compact into a dense matrix. Fine sandy and silty soils have a low permeability so they are susceptible to compaction and so are clayey soils. Subsoil of sand may inhibit the entry of roots which become more thick and stubby, and unable to penetrate for more than a few centimetres due to inherent or induced compaction and rigid particle-particle structure (Batey, 2009). The direction of the compaction stress is shaped by the soil : soil with coarse texture tend to have a vertical dominant stress but soil with finer texture propagate the stress in a multidirectional way. Soil with an aggregated texture prevent compaction in depth (Hamza & Anderson, 2005). In order to determine when is the best time to work the soil with an acceptable degree of damage, the former Soil Survey of England and Wales combined climatic data and soil texture, soil moisture and permeability for each soil (Batey, 2009).

The type of crop may influence compaction as the seeding and harvesting need to be done under conditions favourable to avoid compaction. For instance, root crops are usually harvested during fall when the soil water content is around field capacity. Furthermore, as they have to be lifted from the ground, there is an increase of applied pressure. Legumes are also known to be more sensitive as they need aeration on nitrogen fixation in nodules (Batey, 2009).

Soil compaction & hydrophysical parameters of the soil

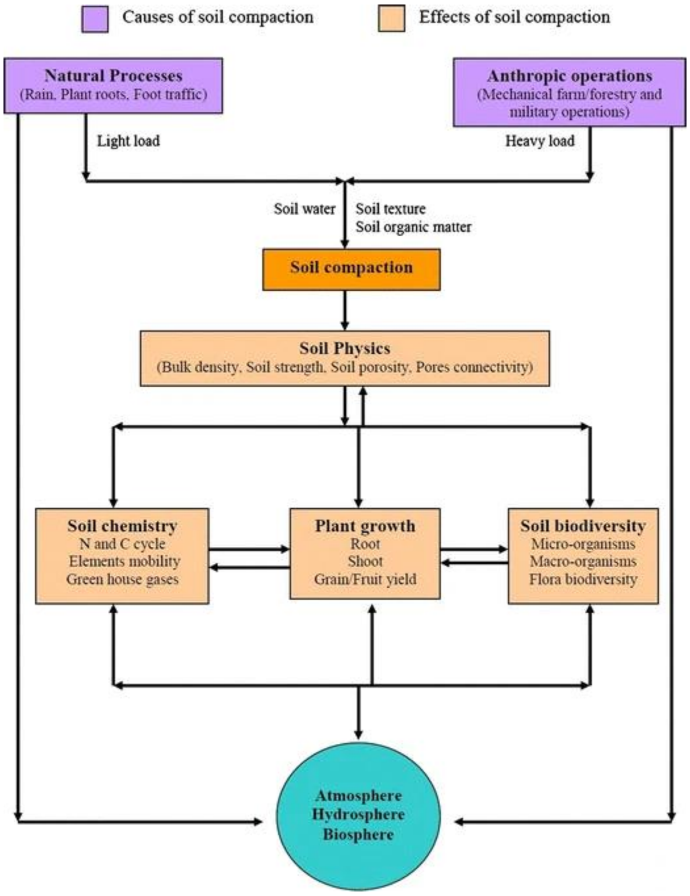


Figure 1 : Causes and effects of soil compaction (Nawaz et al., 2013).

As shown by Figure 1, soil compaction has an impact on several soil physic parameters. It increases bulk density and soil strength, and decreases porosity (Batey, 2009; Indoria et al., 2020). Bulk density is a physical property defined as the mass of dry soil in a known volume (Soil Science Society of America, 2008) and it's frequently used to characterize the soil compactness (Hamza & Anderson, 2005). According to the *Glossary of Soils Sciences Terms*, soil strength is "A transient localized soil property that is a combined measure of a given pedon's, horizon's, or other soil subunit's solid phase adhesive and cohesive status". It reflects soil resistance to root penetration (Hamza & Anderson, 2005). Finally, porosity is the ratio of gas or liquid space in a known volume of soil (Indoria et al., 2020). Among others, compaction influences hydraulic properties of the soil (Batey, 2009). Those properties are important as they describe the soil and its functioning. It also characterize how nutrients, chemicals and pollutants move in the soil. It also determine the water uptake available for plants and the crop growth (Indoria et al., 2020).

The hydraulic properties of the soil are, among other, the soil water retention and the hydraulic conductivity. The soil water retention expresses the ability of a soil to retain water under various pressures. The available water capacity can be deduced out of it. The available water is defined as the amount of water available to plants that can be stored in soil. This parameter helps to select the adapted crops, cropping system and fertilizer application. The hydraulic conductivity defines the ability of the soil to let water through it. The saturated conductivity is the hydraulic conductivity at saturation. This parameter allows to measure drainage, runoff, leaching of nutrients out of the rooting zone and apply the adequate irrigation. The hydraulic conductivity is based on infiltration which describes the time rate at which water percolates through the soil interface (Indoria et al., 2020). The infiltration is a common parameter analysed as water goes through uncompacted soils with aggregates much faster than soils without structure (Hamza & Anderson, 2005).

Soil compaction & soil fauna

As displayed in Figure 1, soil compaction also effects soil biodiversity. Indeed, soil compaction reduces the activity soil biodiversity, particularly micro-organism (Hamza & Anderson, 2005). Soil fauna is the living entity of the soil. It includes eukaryotic, heterotrophic, motile organisms such as earthworms, mites and other but also fungi, bacteria and others smaller organisms. It influences diverse hydraulic properties but is also influenced by them (Görres & Amador, 2021; Indoria et al., 2020). Soil biota is divided in three groups depending on several characteristics :

- Sizes as shown in Figure 2 ;

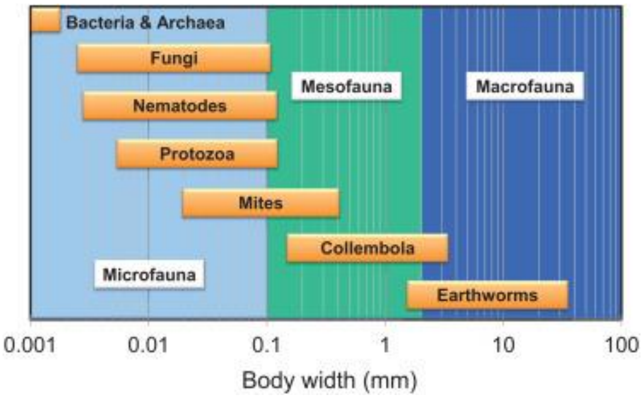


Figure 2 : Organisms dimensions of soil fauna (Görres & Amador, 2021).

- Habitat types :
    - Some organisms are **aquatic**, such as protozoa and nematodes, which live in the pores filled with water ;
    - Others are **aerial**, like microarthropods, living in the pores filled with air ;
    - And others engineer their habitat, mostly earthworms.

Due to their characteristics, each group lives in different size of soil pores. The microfauna is found in the mesopores (30 – 100 µm) and micropores (< 30 µm). Those pores are usually within soil aggregates and retain water at low matric potentials (less than 30 kPa). The mesofauna lives in macropores (> 100 µm) which usually is the space between aggregates that drain easily. As members of the macrofauna are larger than the existing pore structure of the soil, they dig their habitat or use the channels create by other organisms or live on the soil surface (Görres & Amador, 2021).

While feeding, burrowing and moving, the soil fauna develops habitats for the soil microflora, transports microorganisms and decomposes plants parts. Therefore, the soil fauna contributes to the nutrient cycles (Görres & Amador, 2021). Indeed, small soil physical structure may be related to the nature and patterns of trophic interactions in soils as it restricts soil organisms' ability to sense food. The soil's properties define the access to food through the water dynamics and pores among other parameters as shown in Figure 3. Therefore, soil engineers' ability to create channel can influence the food web and the physical properties of the soil (Erktan et al., 2020).

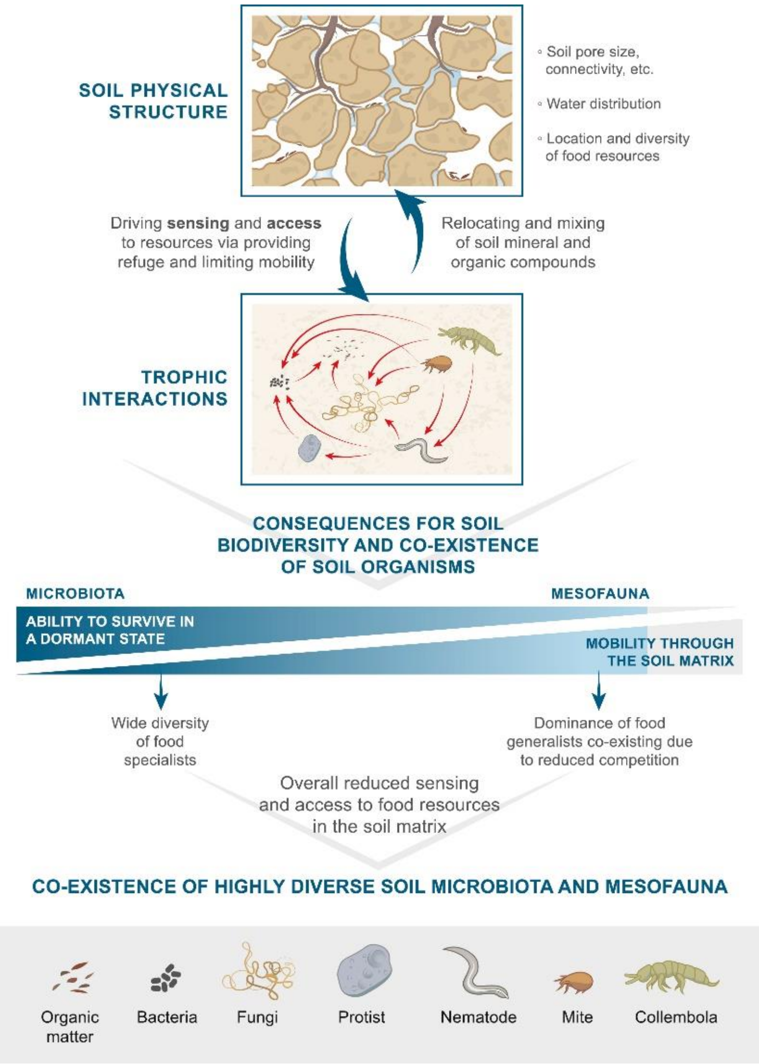


Figure 3 : The influence of soil physical structure on trophic interactions of the soil fauna. (Erktan et al., 2020).

Recommendations for compaction

To prevent or alleviate compaction, one specific agricultural practice can’t be recommended but a combination of them can delay or mitigate the problem. Since soil compaction decreases soil porosity, the solution is to increase soil porosity. Several techniques have been studied such as adding organic matter, controlled traffic farming (CTF), deep ripping or crop rotation (Hamza & Anderson, 2005).

As mentioned above, the compaction depends on the water content, the soil strength and the magnitude of the pressure at the time it was applied. This means that thoughtful planification of the activity on the field may help. For instance, the seedbed preparation can be done when the soil is firm and supportive. Unfortunately, other operations such as the harvest of root crops need to be done at field capacity or wetter which increase the risks of compaction. Compaction can also be avoided or reduced if a rain-soak field is not ploughed or march upon by cattle but under the current farming practices and economics, the use of bigger crop machines is inevitable in order to feed the ever-growing population. Increased compaction degree is then inevitable unless appropriate compensating measures are taken (Batey, 2009). Therefore,

improving land management is vital to ensure that the soil physical conditions are not compromised, especially with the growing population to feed (Hamza & Anderson, 2005).
Another solution is controlled traffic farming (CTF). It consists of minimum permanent traffic lane, so all machinery has the same or modular working track and a precise guidance on the traffic lane. The layout of the permanent lanes is designed to optimize surface drainage and logistics. The benefits of this method include avoidance of traffic induced soil compaction thus greater plant available water and improved soil biology (Bluett et al., 2019). Under controlled traffic, soil water infiltration is similar to natural soil. However, if it is worked with a medium sized tractor, it would reduce infiltration to the level of a long-term cropped soil. Consequently, wheel traffic, rather than tillage and cropping may be the major factor governing infiltration.
In CTF system, wheels tracks represent 20% of the land but losses are compensated with a higher yield (Godwin et al., 2022). Soil compaction during harvesting sugar cane with farm machines can be reduced by controlled traffic or otherwise by limiting axle loads and capacity of individual trailers and using even loading of axles. To conclude, controlled traffic farming greatly reduces soil compaction but may not eliminate it completely (Godwin et al., 2022; Hamza & Anderson, 2005).

Organic matter could help resolve the compaction problem because it retains water which make a rebound against compaction. For this reason, the quantity of organic matter in the soil should be at an adequate level to stabilize the soil structure as its decreases bulk density and soil strength, making it more resistant to degradation. Although it works easily for topsoil, using organic matter to improve subsoil compaction is less common because of the costly techniques to inject organic matter into the rooting zone. Indeed, in order to achieve this, the soil must be ripped to at least 20-30 cm which has a high cost. Green or brown manure as source of organic matter may not be an economically viable option in a high yield environment but beneficial practice on improving soil properties in compacted soil (Hamza & Anderson, 2005).

Alleviating compaction mechanically depends on its depth, thickness and severity. If it's on the surface, cross-tillage soon after a compacting event may control the damage. Bellow topsoil and beyond the reach of surface tillage implements, a deeper treatment is necessary (Batey, 2009). An important practice to eliminate soil compaction is deep ripping or deep cultivation which destroys hard pans and better hard setting soil. One disadvantage of this technique is that the conditions of the soil after the treatment make it vulnerable to re-compaction by subsequent machinery, grazing or through repeated precipitation of fine clays and colloids through wetting-drying cycles, especially in clayey soils. Rainfall explains 67-91% of the re-compaction process as the water filtering through the soil cause the precipitation (Hamza & Anderson, 2005; Hartmann et al., 2008). One way to prevent the undesirable side-effect and to reform the structure of the uncompacted soil is adding a binding or flocculating agent such as gypsum or organic matter. Without it, it's likely that the soil will be recompacted within the first year after ripping. The decrease of the infiltration rate in time after ripping treatment suggests that large soil voids created during the treatment are gradually filled with fine particles and colloids and the soil become compacted again. This can have an impact on yield which can be reduced due to incomplete re-compaction that increases soil strength. Capillarity action may be altered and causes salt to accumulate to the surface because of evaporation. Deep-ripping also reduces groundwater recharge and soil erosion. Finally, the use of this technique is very expensive as ripping the soil is the critical component of removing soil compaction physically (Hamza & Anderson, 2005).

Another contemplated solution is crop rotation. Certainly, plant roots' ability to penetrate is restricted as soil strength increases and ceases entirely at 2,5 kPa. The effect of roots on soil structure depends on diverse factors like the species, the soil constitution, the environmental factors and the soil micro-flora associated. Soil compaction shows in results of analysis by a smaller ratio of fresh to dry mass. Some crops, such as radish and lupin, decrease temporally their roots in diameter after transpiration begins, then increase it again for a short amount of time. This fluctuation in root diameter loosens the compaction (Hamza & Anderson, 2005).

As soil fauna is impacted by compaction, it also impacts it. Indeed, studies show that in time, earthworms play an important role in the regeneration of compacted soil (Yvan et al., 2012). Earthworms influence the ability of transfer in soils by burrowing and bioturbing the soil and creating macropores (Capowiez et al., 2014). In maize field under various organic matter treatment, it was demonstrated that earthworms mass and bulk density were negatively correlated (Binet et al., 1997). Combined to reduced and no-tillage practices that favour earthworm density and activity, compacted soils can be slowly regenerated (Capowiez et al., 2014).

Soil compaction in Thailand

Soil degradation being a worldwide problem, Thailand hasn't been spared either as 6 Mha of the country are considered as degraded soils which represents more than 10% of the surface of the country. Thailand currently faces three challenges : 1) the need to restore and rehabilitate degraded land ; 2) reducing carbon loss and increasing soil carbon sequestration ; 3) promoting community awareness and participation in land management. There is also an interest in soil macrofauna as understanding and managing it improve soil physical characteristics through bioturbation (Nopmanee et al., 2022).

Thailand is an important food exporter since the 20th century despite its unfitted soils for agriculture. Through the development of roads in the 1950s, the possibility to grow cash crops allowed the country to become a leader in Asia (Nopmanee et al., 2022). The government has invested a lot in the soil section. In 1965, the Land Development Department is created to make soil survey, mapping, analysis and experiment. The King of Thailand has also initiated the Royal Project which consists in the reduction of inputs to the soil and considering it as a compartment of a larger ecosystem. The idea is to manage the interactions between the soil and its environment to increase sustainably soil productivity. Thailand additionally launched the South-East Asian network of soil laboratories to increase data quality and comparability. In 2014, it became part of the Global Soil Laboratory Network (GLOSOLAN), in the FAO (Nopmanee et al., 2022).

Regarding regulations, the environment is in Thailand's Constitution and the state should manage the natural resources, the environment and the biodiversity in a balanced and sustainable way and should include the local community to participate and benefit from those too. The government may require environmental impact assessment (EIA) and environmental health impact assessment (EHIA) to undertake projects. As there are over 50 legislations other than the Constitution for the environment, there are some overlapping responsibilities in the administration. Those may result in difficulties to coordinate (Sanooj et al., 2023).

The Enhancement and Conservation of National Environmental Quality Act, B.E. 2535 (1992) (NEQA) is the primary environmental legislation that gives quality standards for water, air, noise and soil. The latter standard is divided in two groups : the soil for agricultural and living purposes and the soil used for other purposes. Yet, there are no criminal sanctions provided by this act if a person degrades the environment bellow the standards but several other different laws provide criminal offences for those who break their provisions. The NEQA also gives the rules, conditions and procedures to prepare and submit the EIA and EHIA reports. According to Sanooj & al. (2023), the NEQA does not punish anyone whom degrades the soil bellow the standards although civil liability may apply if the degradation damages someone else or their property (Sanooj et al., 2023). The Land Development Act, B.E. 2551 (2008) (LDA) gives authority to the Ministry of Agriculture and Cooperatives to regulate contaminated land used for agricultural purposes. This act also provides measures to remediate land contamination (Sanooj et al., 2023).

The latter Ministry has developed a 20-year Agriculture and Cooperative Strategy (2017-2036) which secures the livelihood of Thai famers, grows the sector and sustains the agricultural resources through several goals that include the specialization of farmers and the increase of the potential of the agricultural sector. The Ministry does not have a direct legislation on the environment but it has several policies to sustain it such as organic farming and new theory agriculture and management of natural resources (Ratanakorn et al., 2022). Voluntary standard like Good Agricultural Practices Standards (GAP) are promoted to develop safe and quality agriculture (*Good Agricultural Practices for Food Crop*, 2013). Organic management is promoted through standards and labelization. The labelling process and analysis is free and requires 12 to 18 months of transition and must undergo a full physical inspection at least once a year (*Organic Agriculture*, 2009).

During the last twenty years, urban areas and perennial trees like rubber trees, replaced rice field and forest. Indeed, between 1970 and 1980, as agriculture demand for land increases, forest were converted to agricultural land to plant cash crop since the newly built road network created new economic opportunities. Now, social forestry programs and the Royal Forest Service now largely recover the loss of domain and set management policies. Buddhist monks also restored and preserved large parts as they view forest as place for contemplation and spiritual renewal (Wester & Yongvanit, 2005). As those land use changes increase soil degradation process, there is a need to understand and remediate at this process in order to maintain the farmers' income (Nopmanee et al., 2022). In 2021, the top-three major crops harvested in Thailand were rice with 33,58 millions de tons, sugar cane with 66.28 millions de tons and cassava with 30,11 millions de tons (FAO, 2023).

In the worldwide rice (*Oryza sativa* L.) production for the period of 2011 to 2021, Thailand is ranked 6th with an average production of around 33 Mtons, behind China (209 Mtons), India (169 Mtons), Indonesia (57 Mtons), Bangladesh (53 Mtons) and Vietnam (44 Mtons) according to FAOSTAT (FAO, 2023). Rice production take places in lowlands in Thailand. It has a variable dynamic depending on the region : in the Central and Southern Thailand, rice production is market-oriented whereas in the Northeastern, it is for home consumption and only the surplus is sold. Another difference between Central and Northeastern Thailand is that in Central, fields are irrigated whereas in the Northeast, they are rainfed. Therefore, there is usually only one crop season per year in the Northeast as opposed to the Central part of Thailand where there are several crop seasons per year (Suwanmontri et al., 2020). Rice plants are characterized by a fibrous root system that develop adventitious root. This type of roots has a thin hair-like morphology and grow near the surface of the soil (Sundararajan et al., 2023).

Cassava (*Manihot esculenta* Crantz.) and sugar cane (*Saccharum officinarum* L.) are both cash crops cultivated in the uplands by farmers to increase their income and resist climate-induced loss in income due to lack of rain (Yoshida et al., 2019). For worldwide sugar cane production over the same period as above, Thailand is on the 4th position with 98 Mtons behind Brazil

(746 Mtons), India (361 Mtons) and China (113 Mtons) (FAO, 2023). To harvest sugar cane, two methods are possible, either the "burnt" method which consists in burning the crop before harvesting it and "green" method, currently promoted by the Thai government to reduce air pollution problem. Mostly, farmers still use the "burnt" method due to lack of adapted machinery and hard-work needed for the "green" method (Thuayjan et al., 2022). Sugar cane's root system is defined by three types of roots as presented in Figure 4 : "superficial roots" are in charge of the water and nutrients uptake from surface soil layers ; "buttress root" which are the first roots emerging from the shoot that became thick and grow in the soil at a depth of 1.5 m to anchor the plant ; finally, "rope roots" that are derived from agglomerations of vertical roots and go deeper than 6 m to have access to water reserve (Smith et al., 2005).

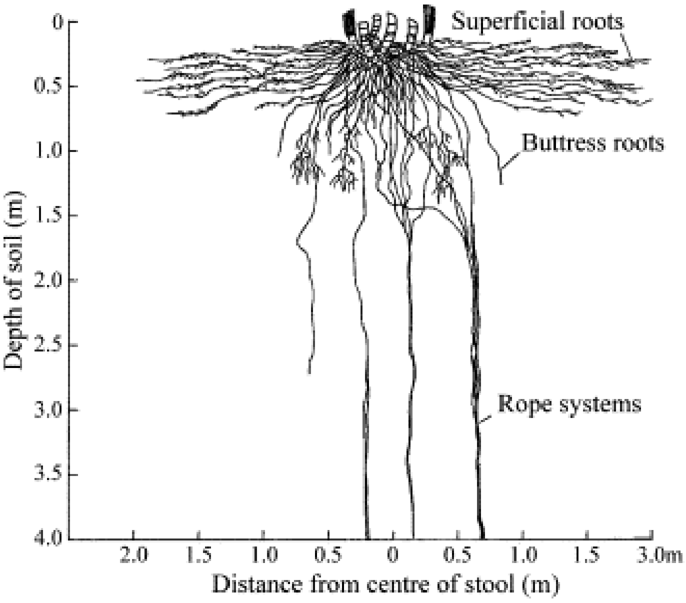


Figure 4 : The root system of an established sugar cane stool. (Smith et al., 2005)

Regarding cassava, Thailand is the first producer in Asia with an average production of 30 Mtons, and in the 3rd position for the cassava worldwide production behind Nigeria (57 Mtons) and Democratic Republic of the Congo (37 Mtons) between 2011 and 2021 (FAO, 2023). Cassava is a resistant plant to drought and acidic conditions grown in the uplands of Thailand. In Northeast Thailand, due to heavy machinery needed and monoculture of the crop on the fields, compaction problems appeared. As cassava is a tuberous plant, the compaction problem is severe because it reduces the starch accumulation as water-holding capacity, porosity and nutrients supply is reduced. The compaction in the subsoil may lead to lower infiltration, resulting in rotting of the roots of the crop. (Kaewkamthong et al., 2014).

II. Objectives

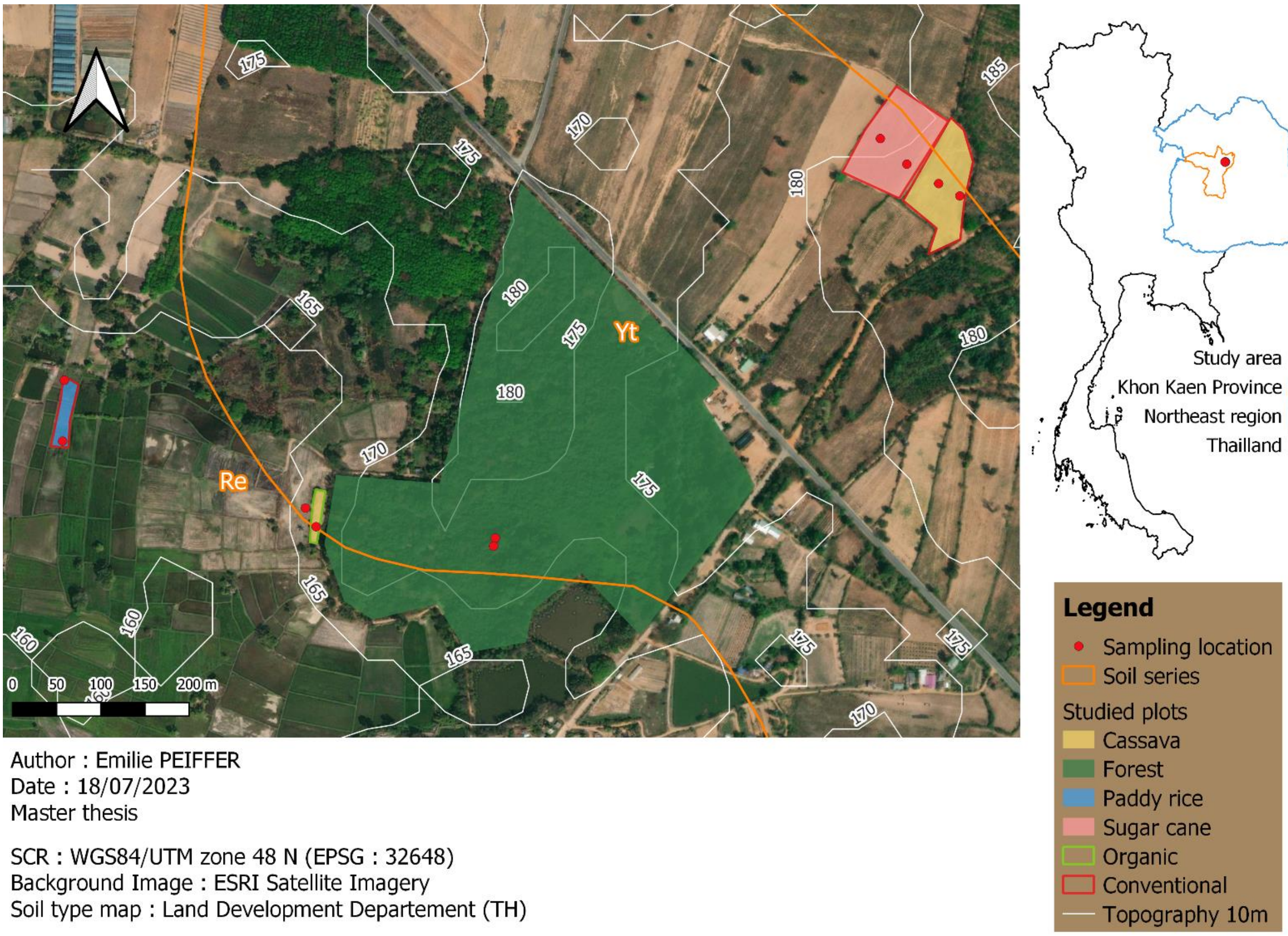
As soil compaction covers a large area in Northeast Thailand and affect the crops and the income of farmers, the objectives of this thesis are to characterize the soil compaction by assessing soil physical and biological parameters and their interaction. The hydrophysical properties studied are bulk density, soil water retention curve, hydraulic conductivity. Regarding the biological indicators, the number of earthworms and casts as well as soil respiration are assessed. Those parameters on several land-uses and managements in Northeast Thailand : sugar cane and paddy rice in conventional management, community forest, and cassava in organic and conventional managements.

III. Materials and methods

a. Experimental site

Soil type and climate

All the land-uses and management were studied in the same area, near the village Ban Hua Beng in the Nam Phong district in the Khon Kaen province of Northeast Thailand. From the soil map acquired from the Land Development Department (LDD) of Thailand, two major soil type are encountered in the study zone : Roi Et (Re) and Yasothon (Yt) (Figure 5). The LDD uses a classification based on the USDA Soil Taxonomy and according to it, both of those soil series are Ultisols which represent 42% of the soil types in Thailand. The Roi Et series is an Aquults Kandiaquults Aeric soil and the Yasothon series corresponds to a Ustults Paleustuls Typic soil.



Author : Emilie PEIFFER
Date : 18/07/2023
Master thesis

SCR : WGS84/UTM zone 48 N (EPSG : 32648)
Background Image : ESRI Satellite Imagery
Soil type map : Land Development Departement (TH)

Figure 5 : Map of the study sites.

As shown in Figure 6, the Aquults and Ustults are typical soil suborders of the Northeast Thaïland (salmon, orange and blue colors in the Northeast). Those soils are both characterized by an horizon A of 20 cm of sandy loam overlaying a B horizon of sandy clay loam. The climate is classified as a “Tropical Savanna” according to Köppen’s classification with an annual mean temperature of 26°C to 28°C and rainfall from 1,100 mm to 1,500 mm. The Roi Et soil series, typically found in the Northeast, is encountered in the lower part of the peneplain where transplanted rice is cultivated during the wet season. It is characterized by a grayish brown A horizon over a pinkish gray or light brown B horizon. The permeability is moderate to low and the runoff is slow. On the other hand, the Yasothon series is often located in the upper part of the peneplain with a cover of dipterocarp and mixed deciduous forest. The color of the first horizon is dark reddish brown and the second is of yellowish red or red color. Those type of soil are excessively drained. On the field, the soil of the conventional cassava and sugar cane appeared to content more sand corresponding to the Yasothon series. On the other hand, the other modalities which presented a finer texture, probably due to the presence of clay particle like presented in the Roi Et series.

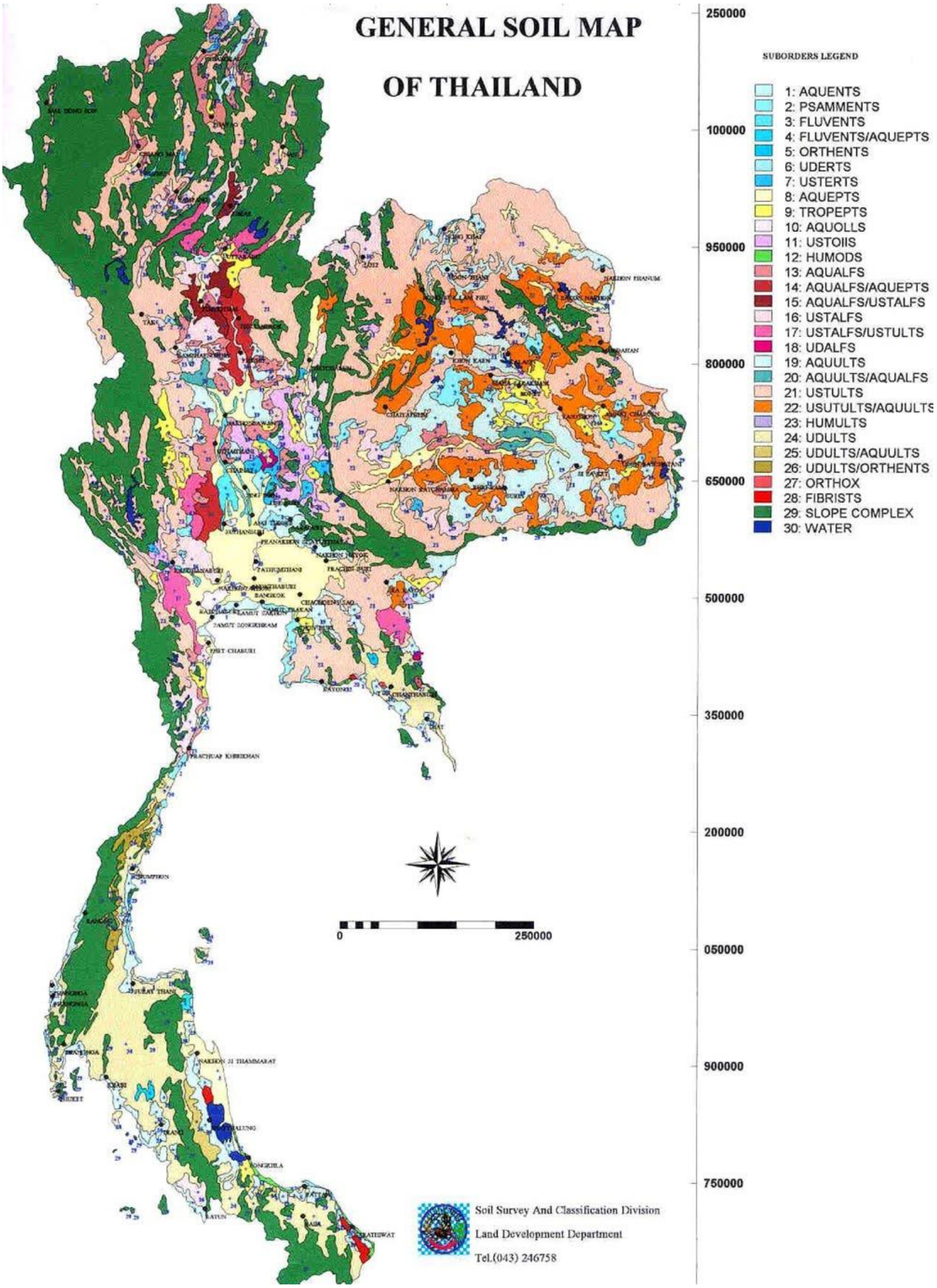


Figure 6 : Suborders soil types of Thailand (LDD).

Crop management

As displayed in Figure 5, the conventional cassava and sugar cane fields are on the upper land of the area whereas the forest, the paddy, and the organic cassava are located on the lower part of this area.

The cassava production takes 10 months. The farmer's yield for this crop is around 3 to 4 tons/rai[1] (18.75 – 25 tons/ha) which is lower than the average : 4 – 5 tons/rai (25 – 31.25 tons/ha). The field is first plowed at a depth of 20 – 30 cm, sowing manure is applied at 200 – 250 kg/rai (1,250 – 1,562.5 kg/ha) to dry the soil for about one or two weeks. The quantity of manure applied is lower than what the Department of Agriculture recommends (500 – 1,000 kg/rai = 3,125 – 6,250 kg/ha). The plot is then ploughed again before planting. The seedlings are prepared to be around 20 – 25 cm long with roots about 10 – 15 cm deep. The planting process started around the 6th or 7th of May 2023 and plants are spaced at 80 cm from each other horizontally and vertically. After 10 months, the cassava is harvested (Figure 7) : farm workers cut the stems then a tractor is used to dig up the cassava roots. The cuts are then sent to be sold at varying prices ; for the past season, the price of cassava was around 3.5 bahts[2]/kg. The cassava in both management is rainfed.

Figure 7 : Harvesting the cassava (Jutatad Rattanapong).

In conventional management, a mix of fertilizer is applied to the crops once every 1 – 2 months after planting. The composition per rai is :

- 100 kg of 46-0-0 (N-P-K) (625 kg/ha)
- 50 kg of 16-20-0 (N-P-K) (312.5 kg/ha)
- 50 kg of 0-0-60 (N-P-K) (312.5 kg/ha)

---

[1] The « rai » is a Thai aera unit. It is equivalent to 1600 m² or 0.16 ha.

[2] The baht is the Thai. 1 baht equals 0,03€.

To manage weeds, the farmer sprays 100 L of flumioxazin at 0.3 g/L per rai (625 L per ha) when planting is finished and another one afterwards. If more weeds grow in the field, it is removed manually. To control pests, the farmer uses wood vinegar at 300 – 400 mL diluted in 25 L of water per rai. The farmer tried to meet the Good Agricultural Practices requirements but failed for the storage of pesticides and recording of management.

For the organic management, the farmer uses manure fertilizer and no herbicide nor pesticide. The farmer started to grow organically because he wanted to try something new and good for his health. He will continue to manage organically but he does not get the organic label from the Ministry. For both field, the same crop was planted for the past two years but five or six years ago, he cultivated sugar cane on that field because the high value of this crop on the market.

Figure 8 : Ploughing machine (Jutatad Rattanapong).

The sugar cane field is prepared by ploughing at around 50 cm deep, tilling the soil for lumps, then raising the furrows at 1.3 – 1.5 m from each other. The planting process involves farm worker digging planting trenches at 1.2 – 1.3 m from each other. Afterwards, cultivars are planted 50 cm apart. As the studied field is managed with chemicals, the farmer applies fertilizer of 15-15-15 at the rate of 50 kg/rai (312.5 kg/ha) during planting and second time at the same rate when the crop is 60 days old. He sprays alachlor 48% W/V EC at 400-600 mL per 60-80 liters of water per rai after planting. Before harvesting, the farmer burns the canes and harvests manually. The farmer does not manage this field according to the GAP. This crop is also rainfed and was planted on the plot for the last two years. The yield is around 9 – 10 tons per rai (56.25 – 62.5 tons/ha) and depending on the market, sold at 800 – 900 baht/ton.

The paddy rice production begins in June. To prepare the field, the soil is ploughed at a depth of 20 – 30 cm then flooded for 1 – 2 weeks to ferment the rice straw left on the field and the weeds. After soaking the seeds in water for 24 hours, the rice of variety Hom Mali 105, is seeded at a density of 25 kg of seeds/rai (156.25 kg/ha) with a rotary cultivator. There is one fertilizer application during the rice reproductive phase at a rate of 37.5 kg/rai of 15-5-25 (234.4 kg/ha). Seven days after sowing, herbicide mixing ‘Butachlo35%’ and ‘Propanil35%’ is applied at a rate of 100 – 200 mL per 25 L of water per rai. Pests are controlled by the application of pyroligneous acid at 400 mL/25L of water per rai. Harvest is around November or when the rice is 120 days old using a combine harvester. The productivity for the rice is around 750 kg/rai (4.7 tons/ha) and the production of the field sampled is sold to the Nam Phong Hospital at 30 baht/kg. This field is not managed according to the GAP but if the hospital requires it one day, the famer will obtain the certification. When there is no crop, the farmer lets his buffalos gaze on the moist field.

The forest where the samples were collected is a community forest named “Don Dong Kam Forest”. Inside, there is a sacred 260 – 270-year-old tree, the “Maduea Kwang Tree”. Its circumference is 6.35 m and its height is around 50 m. When the village of Ban Hua Beng was created around 1895 A.D. by immigrants from two other villages, the monk who lead the immigrants settled down in the area and it was prohibited to cut down any tree from the forest. It is said that those who do not respect this will face misfortune or death.

b. Sampling and measurement strategies

For hydrophysical parameters of this study, two depth were analyzed on each plot : 10 cm and 40 cm. Twelve replicates were sampled on the 18th and the 19th of March 2023, six of them were used for the soil water characteristics and the others six were used to determine the saturated hydraulic conductivity. All samples were weighed fresh after the field campaign then were oven-dry after the experiment and weighed to determine soil moisture and bulk density providing twelve replicates for those parameters. Three replicates of unsaturated hydraulic conductivity per plot were made for both depth. The biological parameters were taken on the 14th of June with six replicates for the soil respiration and three replicates per plot for the population of earthworms and number of casts.

The wet part of the soil water retention curve was assessed in the Soil Physics laboratory of the Agricultural Development Research Center in Northeast Thailand whereas the saturated hydraulic conductivity, the soil water content and the bulk density were assessed in the laboratory of the Department of Soil Science and Environment of the Faculty of Agriculture in Khon Kaen University (KKU). The dry part of the water retention curve was measured in the Soil Physics and Mechanics laboratory of the EnvironmentIsLife CARE (Research and Teaching Support Units) in the Faculty of Gembloux Agro-Bio Tech of Liège University (ULiège).

c. Bulk density

In order to obtain the bulk density of a soil, a known volume of undisturbed soil is taken in a soil core sample, then dried in an oven at 105°C for at least 48 hours. The whole sample is weighed then the soil core is cleaned and weighed afterwards. The bulk density is determined by the following equation :

$$\rho_d = \frac{m_{tot} - m_{cs}}{V}$$

Where :

- m_{tot} is the dry weigh of the soil and the soil core sample (g) ;
- m_{cs} is the weigh of the clean soil core sample (g) ;
- V is the volume of the soil core (cm^3).

d. Water content

Soil volumetric water content is expressed as the volume of water in soil before drying at 105°C divided by the bulk volume of the soil. To acquire it, the first step is a sampling of soil in a known volume soil core. The sample is weighed before being oven-dried at 105°C for at least 48 hours then weighed again. The water content is calculated according the equation :

$$\theta = \frac{m_{tot,wet} - m_{tot,dry}}{\rho_w * V}$$

Where :

- $m_{tot,wet}$ is the wet weigh of the soil and the soil core sample, right after sampling (g) ;
- $m_{tot,dry}$ is the dry weigh of the soil and the soil core sample (g) ;
- V is the volume of the soil core (cm^3) ;
- ρ_w is the density of water = 1 (g/cm^3).

e. Soil water retention curve & pore size distribution

Soil water retention curve

The soil water retention curve expresses the water withdrawn from pressions steps applied to an initially saturated core soil sample. It gives the water disponibility in the soil but also how land management may affect the water availability. On Figure 9, typical soil water retention curve are plotted using the model 1 of Rosetta, a program that estimates the average hydraulic parameters based on textural classes ranked according to the USDA Soil Taxonomy (Schaap et al., 2001). The soil types presented here are sand, loam, clay, sandy loam and sandy clay loam. As mentioned in the Soil type and climate section, the last two displayed soil type are the topsoil layer and the subsoil layer, respectively according to the soil map. Therefore, those soil type will be respectively plotted with the corresponding results.

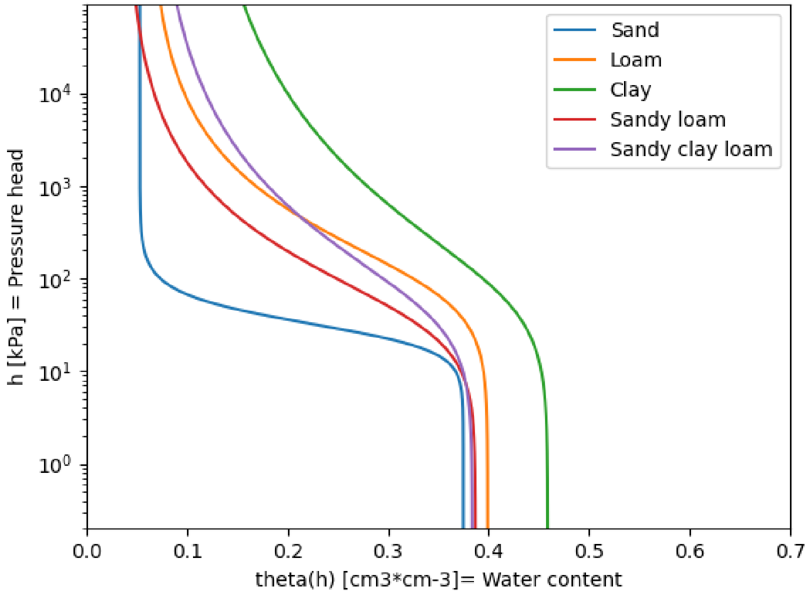


Figure 9 : Water retention curve examples based on the estimated parameters of the model 1 of the Rosetta program.

The plot shows the water content on the abscissa and the matric potential on the ordinates. (Kirkham, 2014b). The water content is the moisture percent by volume in soil, its units are the percentage. The matric potential refers to the potential energy of water in soils due to the forces of adhesion and cohesion between water and the soil matrix (Soil Science Society of America, 2008). When taken positive as in Figure 9, the matric potential is called suction and as suction increases, the water content decreases and the soil gets drier.

Regarding soil compaction, small increase in bulk density due to compaction reduces the available water storage capacity significantly (Ngo-Cong et al., 2021). Compaction induces a reduction of water content at high matric potential and an increase in water content at low matric potential (Figure 10)(Alaoui et al., 2011).

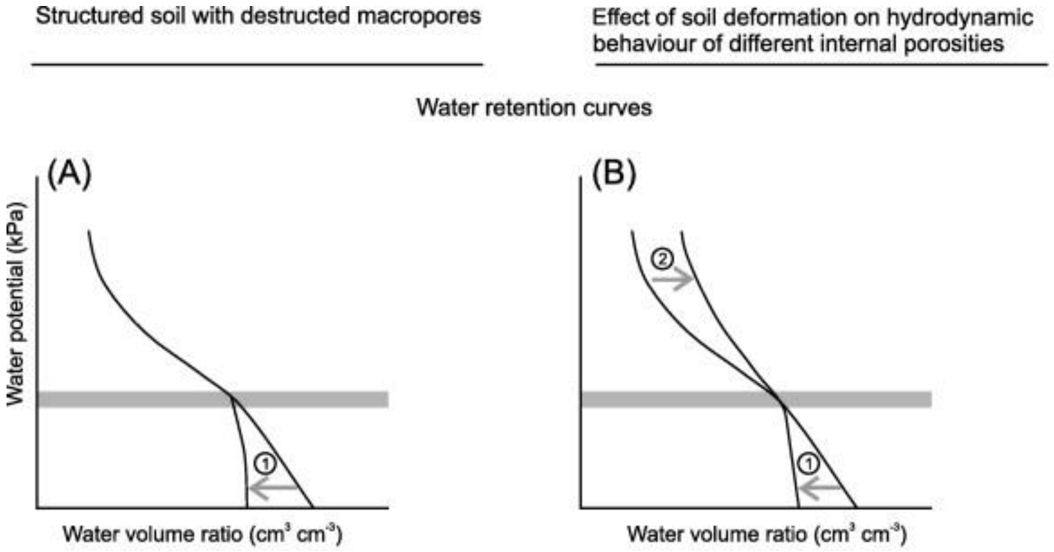


Figure 10 : Simplified outline of the effect of soil compaction on the water retentions curves ; (1) reduction of structural porosity, (2) appearance of relict structural porosity ; gray : the boundary water potential between macropores and micropores (Alaoui et al., 2011)

In this study, a pressure plates apparatus was used at applied pressure of 50, 100, 300 and 1000 cmH_2O which correspond respectively to -4.90, -9.81, -29.42, -98.07 kPa on saturated undisturbed soil samples to draw the wet part of the curve. In order to assess the dry part of the curve, a WP4C Dewpoint PotentiaMeter was used. The replicates used in the WP4C Dewpoint were the same used in the pressure plates apparatus. 50 g of soil from each replicate was wetted with 5 g of distilled water and homogenized in an aluminum container. The container was open to allow water evaporation at ambient temperature. The water potential was measured at two points, one above and one bellow -1,500 kPa. The volumetric soil water content was calculated by multiplying the gravimetric soil water content, the ratio of wet soil mass over the dry mass, with the corresponding bulk density.

To plot the curve, the obtained points were then fitted to Van Genuchten's (1980) formula :

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha * h|^n]^{1-1/n}}$$

Where :

- $\theta(h)$ is the measured volumetric water ($cm^3.cm^{-3}$) ;
- h is the suction taken positive (kPa) ;
- θ_r is the residual water content ($cm^3.cm^{-3}$, ϵ [0 , 0.5]) ;
- θ_s is the saturated water content ($cm^3.cm^{-3}$, ϵ [0.3 , 0.7]) ;
- α is a shape parameter, inversely related to mean pore diameter (cm^{-1}, ϵ [0 , 1])
- n is a shape parameter (no dimension, ϵ [1, 10])

The parameters $\theta_r, \theta_s, \alpha, n$ were fitted using the curve_fit function of the scipy.optimize Python package. The algorithm used was the “Trust Region Reflective” (trf) with the bounds presented above.

Estimation of pore size distribution

An idea of the porosity can be given by the pore size distribution which is obtained thanks to the first derivative of Van Genuchten equation and the equivalent pore diameter. The pore diameter based on Jurin's law about the capillary rise :

$$EPD = -\frac{4 * \sigma * \cos \alpha}{\rho * g * h}$$

Where EPD is the equivalent pore diameter (µm) at a given matric pressure h (kPa), σ is the surface tension of water, α is the angle of the meniscus, ρ is the water specific weight and g is the gravity acceleration. Given that σ is 0.07357 kg.s^{-2} and α equals 0 at 22°C, the previous equation can be simplified to :

$$EPD = \frac{300}{h}$$

The first derivative of Van Genuchten equation gives the slope of the water retention release curve $f(h)$ related the soil potential h (kPa) :

$$f(h) = \frac{d\theta}{d\log(|h|)}$$

The pores diameters are separated according to size with macropores as EPD > 150 µm, micropores with an EPD < 30 µm and mesopores are between these two limits. The pores were also classified hydrologically. Three classes were defined : the drainage pores (> 30 µm), comprising the macropores and the mesopores ; the storage pores (30 – 0.2 µm) and the residual pores (< 0.2 µm) (Alessandrino et al., 2023). Examples of pore size distribution for several soil type and limits in pore diameters are given in Figure 11.

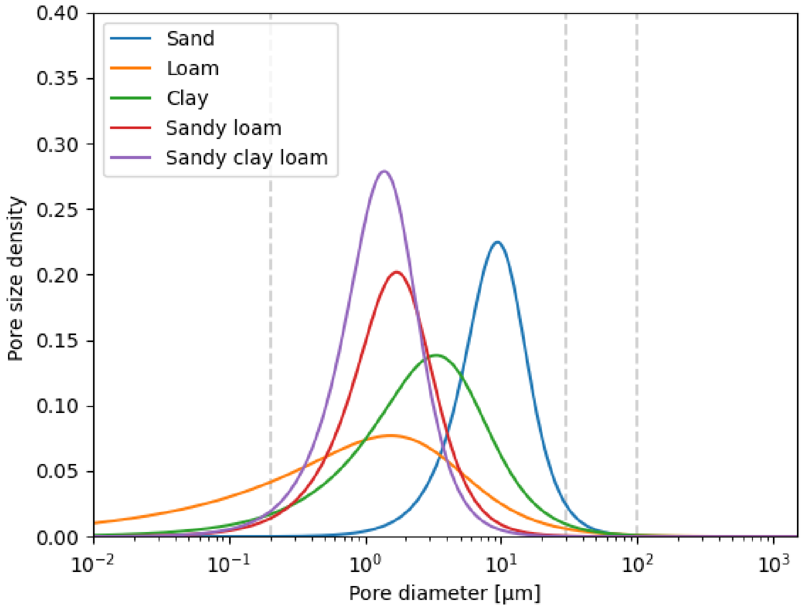


Figure 11 : Pore size distributions examples based on the estimated parameters of the model 1 of the Rosetta program.

f. Hydraulic conductivity

The ability of soil to let a fluid get through under a pressure gradient is represented by the hydraulic conductivity, K, in centimeters per day according to the SI system unit. It is influenced by several biotic factors such as worm holes, cracks and roots and abiotic factors like texture and cracks in the soil. In the surface soil, roots of crops after decay increase the hydraulic conductivity and compaction of soil by human activities or animals increases K (Kirkham, 2014c).

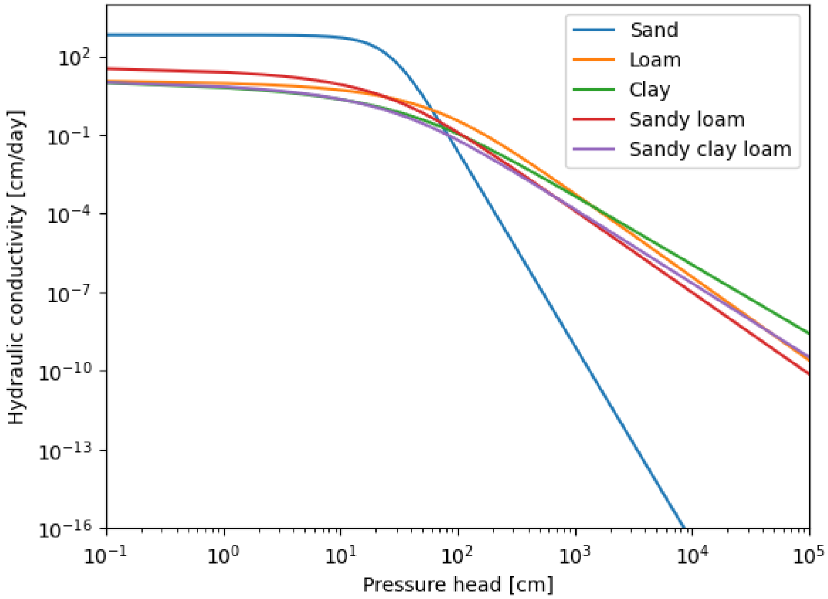


Figure 12 : Hydraulic conductivity function based on the estimated parameters of the model 1 of the Rosetta program.

The hydraulic conductivity curve expresses the hydraulic conductivity, in the ordinates, of a soil under a matric potential, in the abscissa (Figure 12). The hydraulic conductivity is a parameter that was introduced by Henry Darcy who described the flow of a fluid through a porous medium with this equation :

$$Q = \frac{K * A * \Delta p}{L}$$

Where :

- Q is the flux (quantity of water per second) ($cm^3.s^{-1}$) ;
- A is the cross section (cm^2);
- Δp is pressure difference between the top and the bottom of the sample (cm);
- L is the length of the sample (cm) ;
- K is the permeability coefficient ($cm.s^{-1}$).

Saturated hydraulic conductivity (K_{sat})

For this, on one hand, the saturated hydraulic conductivity was determined in laboratory. The saturated hydraulic conductivity is the hydraulic conductivity of a saturated soil. In this case, this parameter was determined in laboratory using a homemade constant-head permeameter presented in Figure 13, on saturated undisturbed soil samples. It was calculated with the previous equation. Isolating K, Darcy's law becomes :

$$K_{sat} = \frac{V * L}{A * t * h}$$

With :

- V, the volume of water that goes through the samples (cm^3) ;
- K_{sat}, permeability coefficient/hydraulic conductivity (cm.day^{-1}) ;
- $h = h_{top} - h_{bot}$, the height difference between the bottom and the top of the sample (cm) ;
- A, the section of the sample (cm^2) ;
- L, the length of the sample (cm) ;
- t, the time it took water to go through the soil (day).

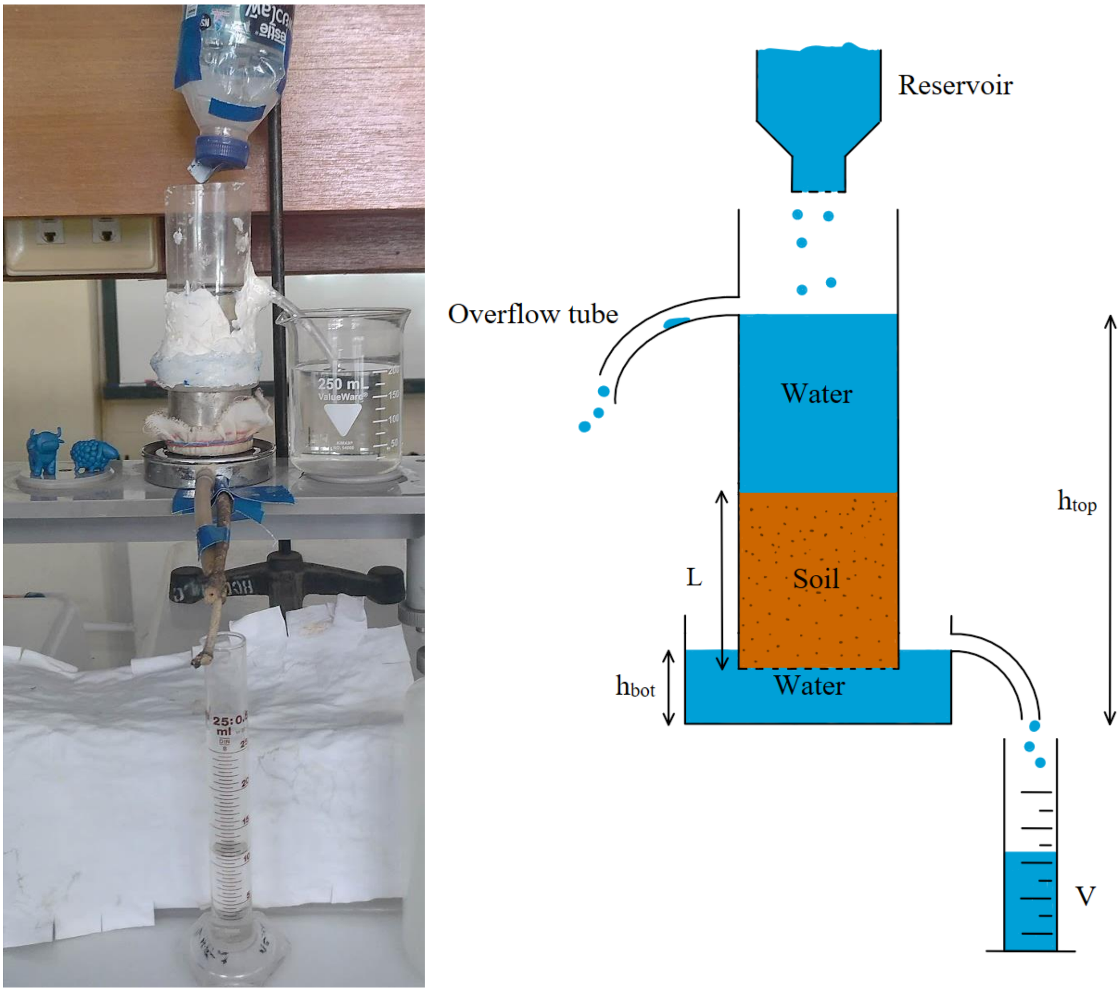


Figure 13 : a) Picture of the home-made constant-head permeameter ; b) scheme of the device

Unsaturated hydraulic conductivity $(K(h))$

On the other hand, during the collection of the samples, the unsaturated hydraulic conductivity was measured with a MiniDisk infiltrometer on the field. A suction rate of 2 cm was applied and replicated three times on each parcel for the two depths mentioned above. The initial volume was registered then volume in the reservoir was noted every 30 seconds. The corresponding hydraulic conductivity was estimated using the R code developed by Sara Acevedo and Carolina Giraldo (Faculty of Engineering Sciences, Universidad Católica de Chile) (https://zenodo.org/record/8001894).

The obtained points were plotted in a hydraulic conductivity curve using Mualem's formula :

$$K(h) = \frac{K_{sat} * \{1 - (\alpha * h)^{m*n} * [1 + (\alpha * h)^n]^m\}^2}{[1 + (\alpha * h)^n]^{m*l}}$$

Where :

- h is the matric potential (kPa) ;
- $K(h)$ is the hydraulic conductivity at matric potential h (cm.day^{-1}) ;
- K_{sat} is the saturated hydraulic conductivity (cm.day^{-1}) ;
- α is a shape parameter, inversely related to the air entry suction (cm^{-1}) ;
- n is a shape parameter and measure of the pore size distribution (no dimension) ;
- m is also an empirical and here equals $1 - 1/n$ (no dimension) ;
- l is pore-connectivity parameter and equals 0.5 for many soils (no dimension).

In the case of this study, with one point of unsaturated conductivity and the corresponding saturated hydraulic conductivity acquired by the methodology previously presented, the function was adjusted fitting the n parameter using the curve_fit function form the scipy.optimize Python package. The α parameter was taken from the soil water retention fit and the value saturated hydraulic conductivity, K_{sat}, was taken from the corresponding composite sample.

g. Soil fauna

Regarding the soil fauna parameters, the soil collection were done on the 14th of June 2023. The experiment and the field work were supervised by Yarapon Puttakot.

Soil macrofauna was assessed by counting the number of earthworms as presented by Pelosi et al. (2014). At least five meters from the border of the field, vegetation was removed from a 1 m x 1 m square. With a watering can, a solution of 300 g of mustard diluted in 10 L of water was applied on the surface of the square. During 15 minutes, the number of earthworms was registered. Afterward, the same solution of 10 L was applied again and the earthworms were counted for another 15 minutes. The numbers of casts per square were also enumerated. Three replicates per plot were made.

The methodology to measure soil microbial activity was inspired from the FAO *Standard Operating Procedure for Soil Respiration Rate* (2023). It comprised the measuring of the CO_2 production of soil by trapping the CO_2 in an alkaline solution (NaOH) which produces Na_2CO_3. The carbonate is then precipitated with $BaCl_2$ and the NaOH left is titrated with HCl. The amount of NaOH initially present minus the amount remaining at the end of the incubation period is used to calculate the amount of CO_2 released from the soil.

In concrete terms, 20 g of soil were put in a jar. Then, 10 mL of NaOH were poured in a small beaker which was hung with a string in the upper part of the jar, as shown in Figure 14. The jar was closed rapidly once the system was secured. After 24 hours, the beaker was taken out and jar cleaned. Five milliliters of $BaCl_2$ 0.5M and three to four drops of phenolphthalein indicator was added to solution of the beaker. The solution was then titrated with HCl 0.05 M. In this study, six replicates were done.

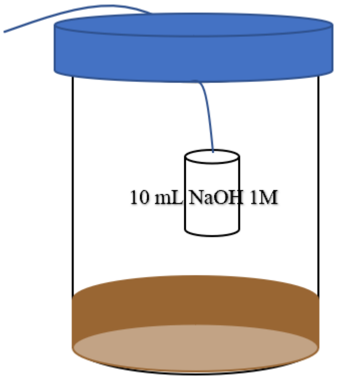


Figure 14 : Jar dispostion (Yarapon Puttakot)

h. Statistic analysis

Boxplot analysis were done on the bulk density, soil moisture and hydraulic conductivity data to remove outliers. The influence of the land use and the management on all the studied properties was evaluated by a two-way analysis of variance (ANOVA) between land-uses/management and depth using R 4.2.1. When possible, a Shapiro and Wilk test was performed to test the normality of the dataset and a Levene test to test the equality of variance. When the results showed a significative difference, the Student-Newman-Keuls (SNK) method was applied to group the mean of the factors in distinct groups. Finally, to see if variables are correlated to each other, a Principal Component Analysis (PCA) was done using the Factoshiny package. As the number of replicate was not the same for all the observations, six replicates per factor were used. For the bulk density and the soil water content of the first sampling, the mean was set as the value for each replicate. For the soil biology parameters which had only three replicates, the missing values were plotted using a two-dimension PCA model.

i. Data loss

Due to mishandling, the dry weigh, the weigh of the kopeckies and the weigh of the covers of the kopeckies of all the hydraulic conductivity samples and the soil water characteristic samples of the cassava in both management and depth and the subsoil sugar cane samples were lost and non-recoverable.

A second campaign of 57 samples was then planned on the 14th of June, the same day the soil biology analysis were undertaken. The field conditions changed as the rainy season had just begun. For the first campaign, the last rain was on the 11th of January, more than two months before the sampling whereas a rain of 42 mm fell the day before the second sampling. On the conventional cassava and sugar cane fields, new plants were cultivated for the new growing season. The same plants were cultivated on the same plots. The organic cassava was harvested and new cassava plants were raised. The paddy field was on the same state as the first campaign from the agriculture view since the farmer waited for us to do the sampling before flooding the field and starting the season. From a visual aspect, the forest conditions did not appear to have changed. As it rained the day before, the soil is expected to be moister than during the first campaign. Those changes in land-use and climate suggest the possibility of a difference between the samples of the first and the second campaign.

In order to measure the dry end of the soil water retention curve, most of the soil from the kopeckies was put into bags and sent to Belgium to continue the analysis. The same treatment was applied to the samples from the second campaign without any change in methodology between before and after the data loss. This allowed to have 87 replicates of the “soil bag transfer treatment”. With the dataset of the dry mass calculated according to the method described for the Bulk density and the mass in the bags, a linear regression was plotted. The R^2 was observed and the probability associated to an T-test of Student was calculated. The hypothesis of that test was that there were no differences between the calculated dry mass and the mass in the bag. For the weigh of the kopeckies and covers, the missing data was replaced with the mean value of the possessed samples.

IV. Results

a. Data recovery

As shown in Figure 15, there is a strong linearity between the dry mass calculated and the dry mass of soil in the bags. The R-squared value is 0.9724 which means there is an error of less than 3%.

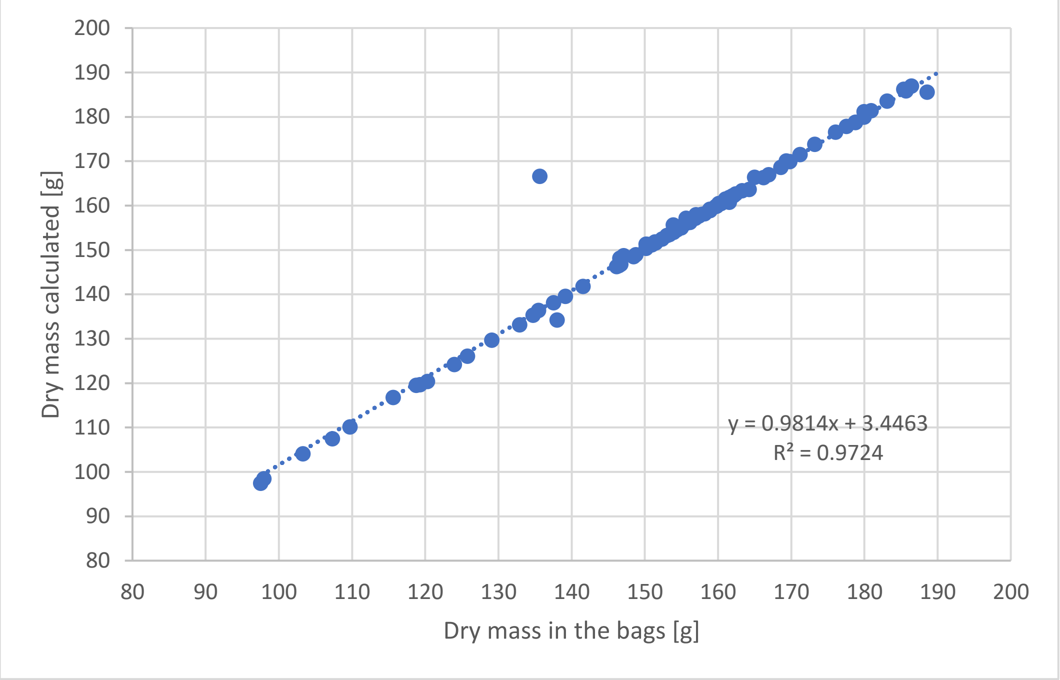


Figure 15 : Linear regression between the calculated dry mass and the mass in the bags

The result of the Student test between the observed dry mass and the one predicted by the model has a p-value of 0,4938. This means that there is no significant difference between the predicted data and the observed data. The predicted dry mass from the mass in the bags was therefore used for the analysis.

b. Bulk density

First sampling campaign (18th and 19th of March 2023)

Regarding the whole dataset of the first campaign, the hypothesis of equality of variances is not accepted. The normality is confirmed for every modality except the topsoil and subsoil conventional cassava. The two-ways ANOVA proves the presence of an interaction between the factors. The depths are then analyzed separately. The Figure 16 a) and b) represent the bulk density on the topsoil and the subsoil of the studied land-use for the samples collected during the first campaign.

About the topsoil, the equality of variance is not confirmed and the normality for all modalities is accepted. The analysis of the variance demonstrates a very highly significant difference between modalities with a p-value of 5.85e-7. Thanks to the Student-Newman-Keuls test, the data is divided in one group of three : conventional and organic cassava with sugar cane with bulk densities around 1.5 g/cm³ and two standalones : the paddy rice modality with 1.38 g/cm³ and the forest modality with 1.26 g/cm³.

In the subsoil, the normality for all modalities except the conventional cassava, and the equality of variances of all are confirmed. The ANOVA shows a very highly significative difference between the means with a p-value of 6.07e-9. The Student-Newman-Keuls analysis make one group with the organic cassava and the forest with bulk densities of 1.52 g/cm³ and 1.49 g/cm³ respectively, significantly different from the other modalities. The sugar cane (1.69 g/cm³) and the conventional cassava (1.61 g/cm³) are also set significantly different from each other. With a bulk density of 1.66 g/cm³, the paddy rice is classified as significantly different from the forest and organic cassava group but not from the conventional cassava nor the sugar cane.

Altogether, it can be observed that the subsoil bulk density is higher than the topsoil for every land-use. Sugar cane, forest and paddy field show important increase in bulk density between topsoil and subsoil (+ 0.17 g/cm³, + 0.23 g/cm³ and + 0.28 g/cm³ respectively). The organic cassava presents the lowest difference between both depths. Forest always have the lowest bulk density whereas the highest in both depths are sugar cane and conventional cassava.

Second sampling campaign (14th of June 2023)

Concerning the results of bulk density for the second campaign, the entire dataset is considered to be normal populations with an equality of variance. The two-way ANOVA shows an interaction between depth and land-use so one-way analysis for the land-use factor were done for both depths.

For the topsoil depth, the analysis displays a very highly significant difference between the modalities of the data with a p-value of 2.78e-06 and the Student-Newmans-Keuls method separates the forest from the rest of the modalities. Indeed, as shown in Figure 16, the forest has bulk density of 1.19 g/cm³ while the other modalities have bulk densities around 1.55 g/cm³ (1.57 g/cm³ for the conventional cassava ; 1.55 g/cm³ for the organic cassava and the sugar cane and 1.53 g/cm³ for the rice).

Regarding the subsoil data, there is a highly significative difference between the modalities as the p-value is 0.001. The SNK method shows significant differences between the sugar-cane (1.82 g/cm³) on one side and the organic (1.57 g/cm³) and conventional cassava (1.67 g/cm³) and the forest (1.67 g/cm³) on the other side. A significant difference between the paddy rice (1.78 g/cm³) and the organic cassava is also displayed.

For this campaign, the forest presents the lowest bulk density in the topsoil and the second lowest in the subsoil. The same tendency of increasing density with increasing depth is highlighted especially for the sugar cane, the paddy rice and the forest with an increase of 0.27, 0.25 and 0.48 respectively. Once again, the organic cassava shows the lowest difference between topsoil and subsoil.

Global analysis

Overall, the bulk density increases with depth. This is commonly illustrated over various land-uses (Dutta et al., 2018; Gopinath et al., 2022). The bulk density for most land-uses rises between the first and the second campaign. This is presumably due to the fact that the cropping season has just started. Therefore, farming operation, performed as describe in the Crop management section, increased bulk density. However, for the paddy rice, the season had not started yet but since the farmer let his buffaloes graze on the wet field, this may enhance the bulk density (Batey, 2009; Hamza & Anderson, 2005).

The FAO & ITPS (2005) defines a threshold of 1.7 g/cm³ from which only negative effects of bulk density are observed. Regarding the results for the agricultural plots presented above, the bulk densities are very close or over this threshold, especially in the subsoil. This could indicate a high degradation and could lower the yield of the crops.

The conventional cassava and sugar cane display important bulk density. This could be due to the soil texture of those plots which appear sandier than the others plots (Woldeyohannis et al., 2022). Indeed, studies show that bulk density decreases with higher clay and, to a lesser extent, silt content (Díaz-Zorita & Grosso, 2000; Jones, 1983; Xu et al., 2017).

As for the forest, it usually presents the lowest bulk density as often found for natural vegetation and forest systems (Biswas et al., 2012; Shrestha et al., 2004). Among other parameters, Ito et al. (2014) highlighted the role litter plays in lowering the bulk density by studying the affect of litter removal through the years.

Sugar cane plot presents high bulk density results. This may lead to reduce yield in the future as this plant is sensitive to compaction. Indeed, it reduces its ability to capture water and nutrient (Barbosa et al., 2021; Pankhurst et al., 2003). This trend is reinforced by monoculture over the years (Otto et al., 2011).

Although less than sugar cane (Reichert et al., 2021) and less than most tuber crops (Howeler et al., 1993), cassava plants are also sensitive to compaction as it reduces the starch accumulation in its tuberous roots (Kaewkamthong et al., 2014). This is enhanced with subsoil compaction due to intensive tillage. The lower topsoil bulk density for both cassava could be explained by the tillage process that reduces compaction in this layer (Pantoja et al., 2019). In that study, the cassava without fertilizer shows the lowest bulk density. Despite no significant increase in yield, a study on the management and deep-ripping of the soil conducted in Northeast Thailand presents an increase in plant survival rate with deep-ripping and soil conditioner application for two years. The alleviation of compaction is located above 50 cm deep, resulting in good conditions for the roots but poor yield and crop quality (Kaewkamthong et al., 2014). They also highlight that without regular deep-ripping, the soil returns to a compacted state two or three years after. Seena Radhakrishnan et al. (2022) studied the impact of cassava management on yield and soil quality. Their results show that organic management does not alter the bulk density but increase the soil quality index and the yield.

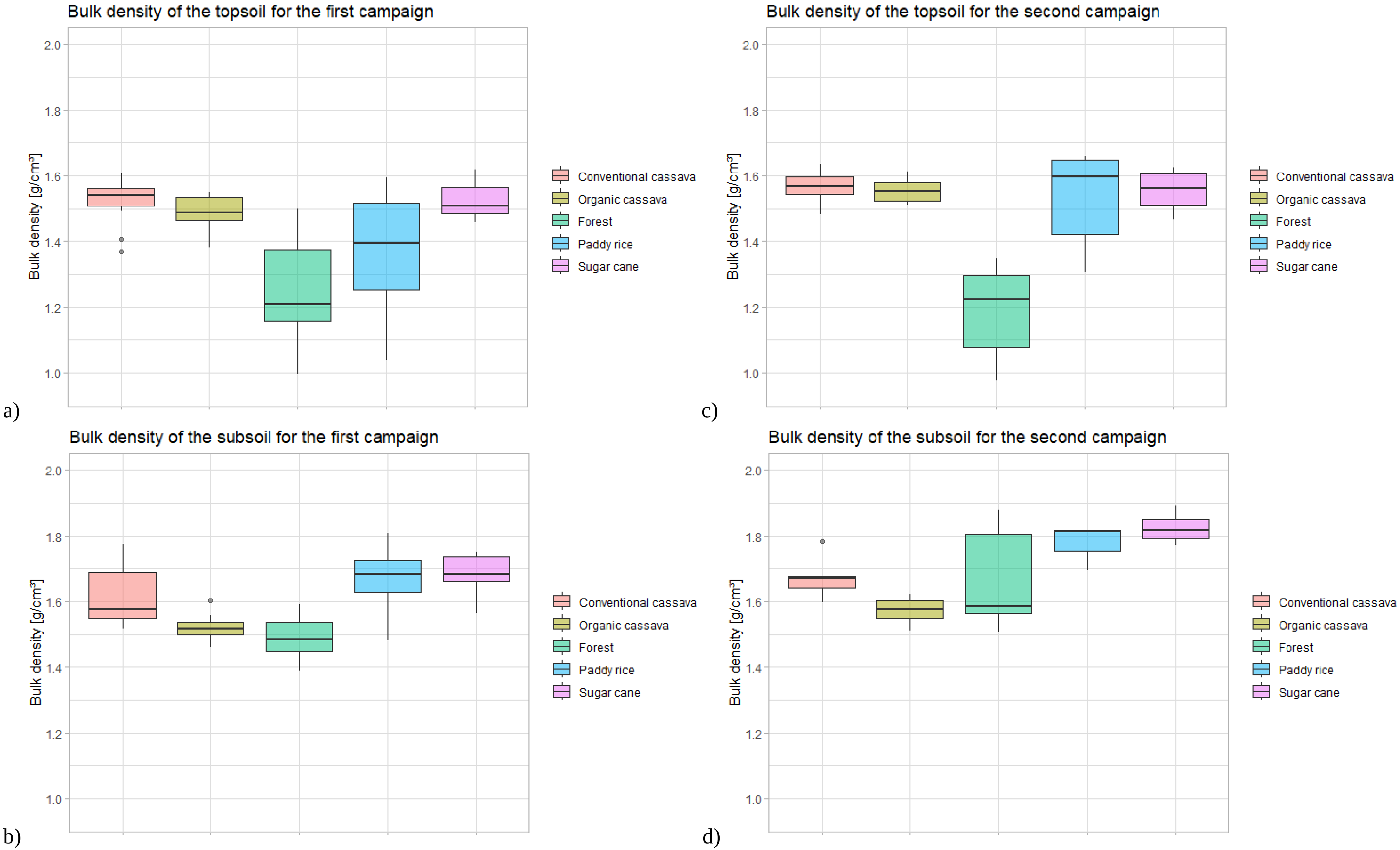


Figure 16 : Bulk density of all land-uses for each depth and campaign. a) first campaign, topsoil ; b) first campaign, subsoil ; c) second campaign, topsoil ; d) second campaign, subsoil.

c. Soil water content

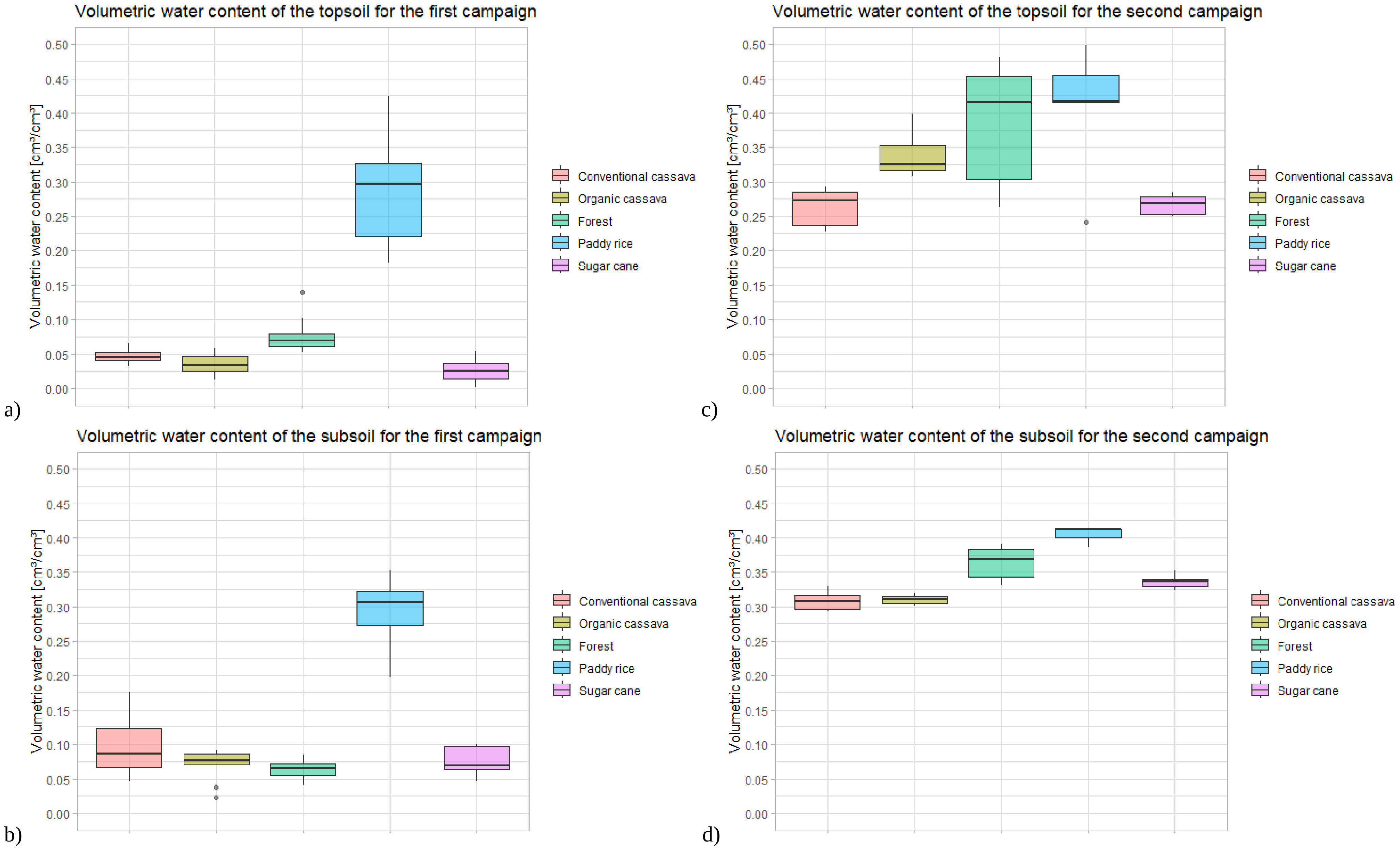
First sampling campaign (18th and 19th of March 2023)

Negative results are obtained for this campaign. Four are in the topsoil organic cassava, one in the subsoil of the forest and one in the subsoil of the sugar cane. This has no physical sense and is presumably due to the approximation made for the data recovery. The estimation of the missing data has its highest impact in this analysis because the estimations are on the weight of the covers and the kopeckies, which are replaced by the mean values of the remaining data, and the dry mass which is replaced by the prediction explained in the Data recovery section. For those reasons, the outliers were removed from the dataset displayed in Figure 17. It highlights that this data must be analysed with caution. In this case, the data was kept to show the important difference in moisture content between the first campaign and the second campaign.

Second sampling campaign (14th of June 2023)

The statistical analysis does not reveal any interaction between the land-use management factor and the depth as the p-value equals 0.055. However, the land-use management factor is very highly significant and the SNK method divides the modalities in two groups : one side, the paddy rice and forest modalities with the higher means and on the other side, the sugar cane and both cassava with the lower ones.

The organic cassava, the forest and the paddy field present higher water content in the topsoil than in the subsoil. This may be explained by a higher clay content due to the difference in soil type and different infiltration rate from the last rain. Larger difference between topsoil and subsoil is exposed in the sugar cane and conventional cassava land-use, probably due to high drainage capacity of those soils. Comparing results from both campaign, even if the first campaign dataset is not relevant, the difference between the two is important. As the first campaign took place at beginning of the dry season and the end of crop season, there were no plants on the field whereas for the second campaign, new crops were planted. The presence of plants and rain explains this difference (Garcia-Montiel et al., 2008).


a) Volumetric water content of the topsoil for the first campaign

b) Volumetric water content of the subsoil for the first campaign

c) Volumetric water content of the topsoil for the second campaign

d) Volumetric water content of the subsoil for the second campaign

Figure 17 : Volumetric water content results. a) first campaign, topsoil ; b) first campaign, subsoil ; c) second campaign, topsoil ; d) second campaign, subsoil.

d. Soil water retention curve & pore size distribution

The detailed plots for each land-use is in Appendix 5-9. The mean obtained soil water retention curves for each land-use along their corresponding pore size distribution are presented in Figure 18. As it can be observed, the specific behaviour of each relationship of land-use/soil would have been lost if the information given by the Rosetta model were used. The boxplots represented in Figure 19 & Figure 20 highlight the differences in the Van Genuchten parameters. Regarding the residual soil water content (θ_r), the analysis reveals no significant difference between depth but very highly significant different between land-uses. The SNK method groups the forest and the paddy rice with significantly higher values than the other group comprising the cassava in both management and the sugar cane. This classification partially results from the soil texture. Indeed, the forest and paddy rice presenting finer texture than the soil type of the conventional cassava and sugar cane could result in a higher capacity to retain water. The type of crop probably plays a role too as the organic cassava shows lower values than the forest and rice that are on the same soil type.

For the saturated soil water content (θ_s), the interaction between the depth factor and the land-use factor is very highly significant. Therefore, the dataset is subdivided according to the depth and significant differences between land-use are highlighted for both depth. In the topsoil, the conventional cassava and the paddy rice present significantly higher values than the rest of the modalities. In the subsoil, the organic cassava and the paddy rice are in the higher group significantly followed by forest then conventional cassava. The sugar cane modality is classified between the last two modalities without being significantly different from them.

For the α parameter, there is an interaction between depth and land-use. In the topsoil, the conventional cassava is significantly higher than the other modalities and in the subsoil, no distinct group is highlighted although the land-use factor is significant. Since this parameter is related to the air-entry pressure, the difference is observed in the pore-size distribution (Figure 18 b)) with the conventional cassava presenting larger pores than the rest of the modalities (Alessandrino et al., 2023). As for the n parameter, land-use modalities are separated in two groups in the topsoil. Paddy rice and forest show higher values than the other modalities. Regarding the subsoil, only the paddy rice modality is significantly higher than the other modalities.

Looking at the pore size distribution, the forest and the rice present high density of storages pores in both depths and almost none in the others classes. This does not explain the higher residual water content than the others modalities as the water in storages pores would drain and high residual water content would be explained by pores in the residual class. However, the equation used to plot the diameter is an approximate of the reality. In the topsoil, the conventional cassava presents high densities of macropores and mesopores whereas in the subsoil, micropores in the storage pores are dominants. The density of meso- and macropores also explains the high saturated soil water content of the conventional topsoil cassava. The sugar cane presents a similar trend of pore size distribution between both depth with a majority of storage pores of around 6-8 µm of diameter. The organic cassava shows storage pores with diameters around 3 µm in the topsoil while in the subsoil it is around 10 µm. The organic cassava and sugar cane also presents pores classified as mesopores. The sugar cane and cassava in both management present type of pores is in the drainage category, showing then a higher drainage capacity than the forest and the paddy rice in which most pores are in the storage category. This reflects the capacity of those soils to retain water for the plants (Alessandrino et al., 2023).

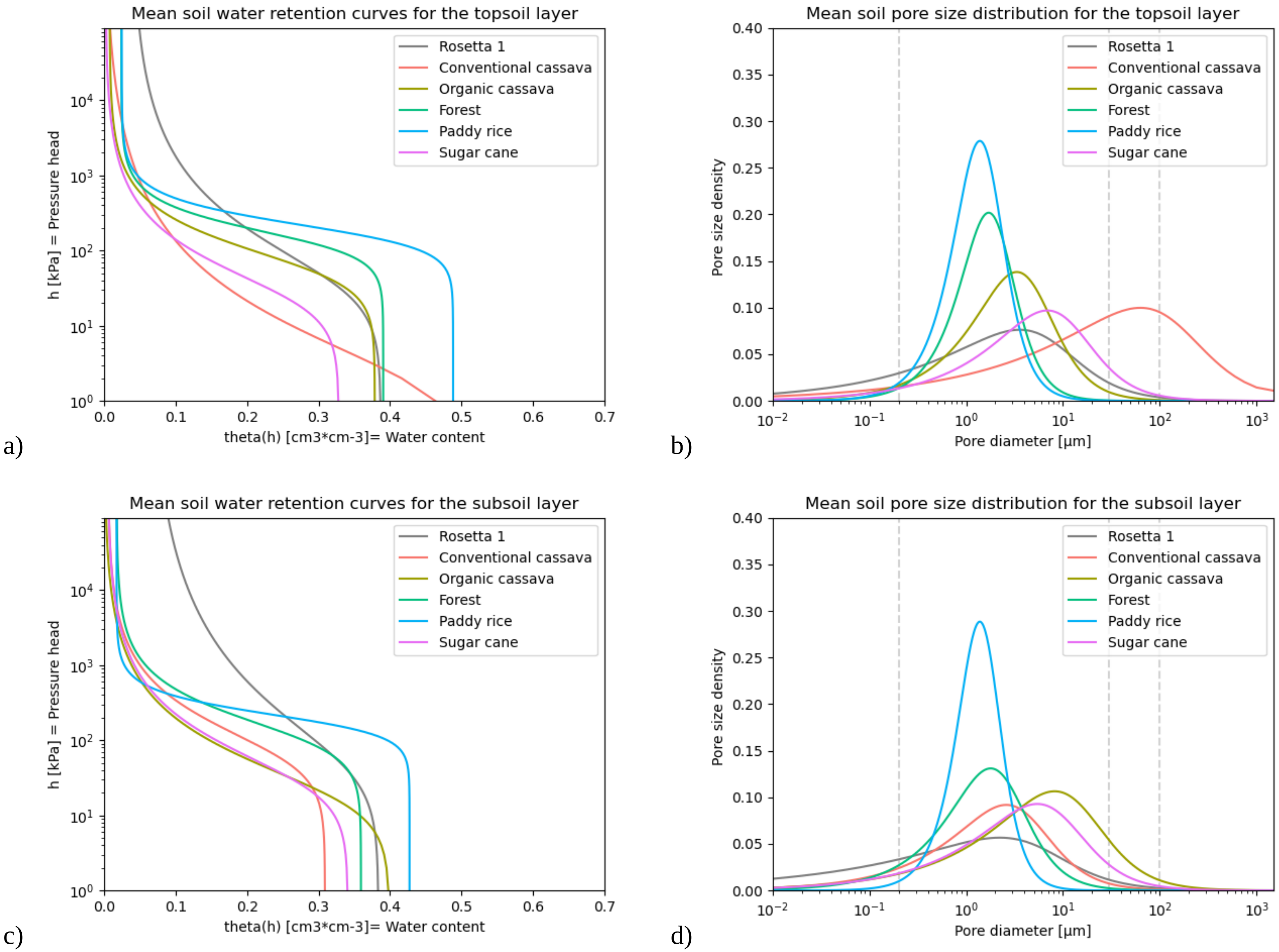


Figure 18 : Mean soil water retention curves per land-use a) for the topsoil, c) for the subsoil and their corresponding pore-size distribution b) for the topsoil and d) for the subsoil. The Rosetta 1 curve uses the Van Genuchten parameters based on the soil type mentioned on the soil map. The grey dotted lines divide the pore classes : macropores with diameter > 150 µm and mesopores with diameter between 150 µm and 30 µm which represent the drainage pores ; micropores < 30 µm which is divided in two hydraulic classes : > 0.2 µm are the storage pores and < 0.2µm are the residual pores.

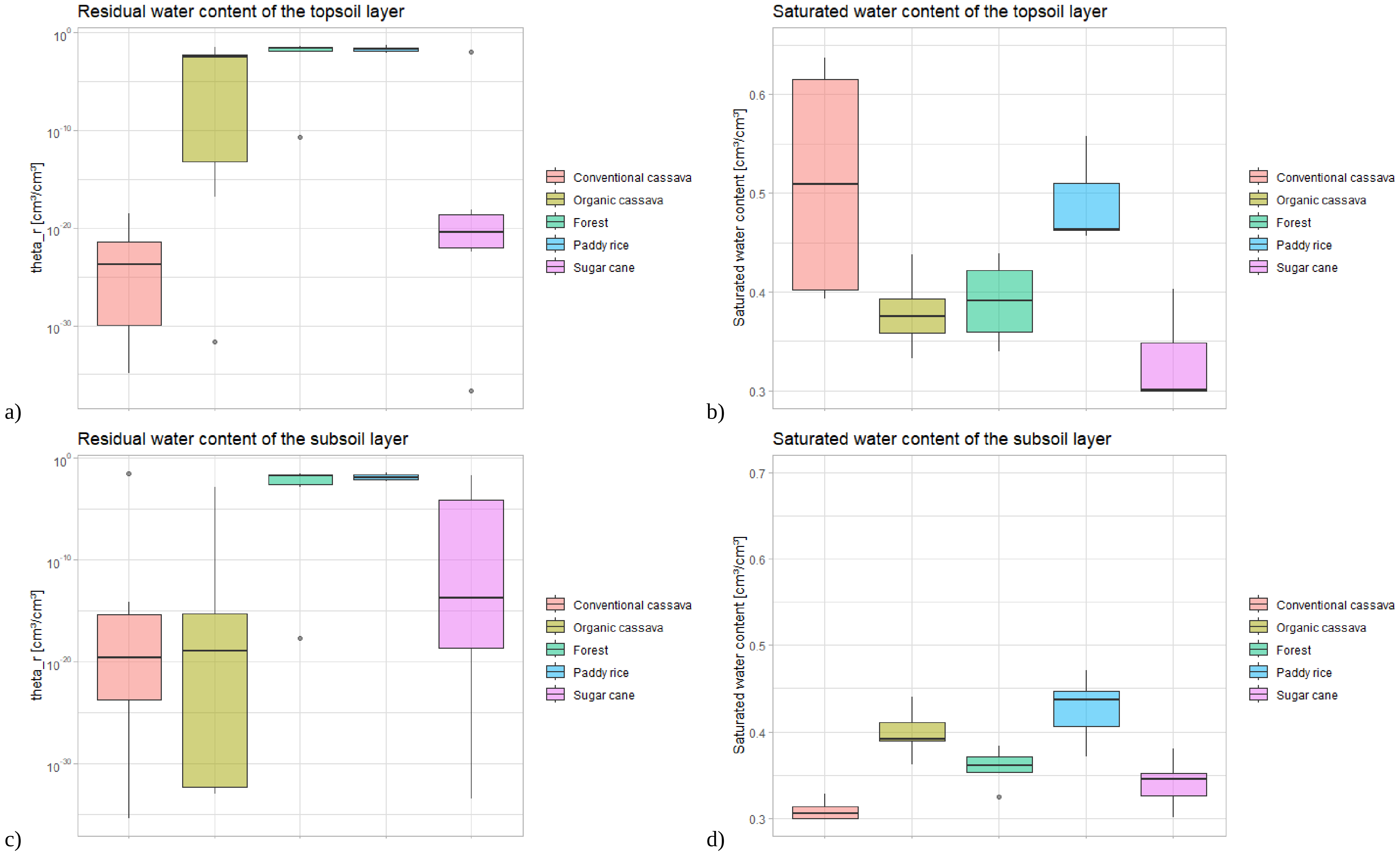


Figure 19 : Residual water content (a & c) and saturated water content (b & d) of the fitted curves for the topsoil (a & b) and the subsoil (c & d)

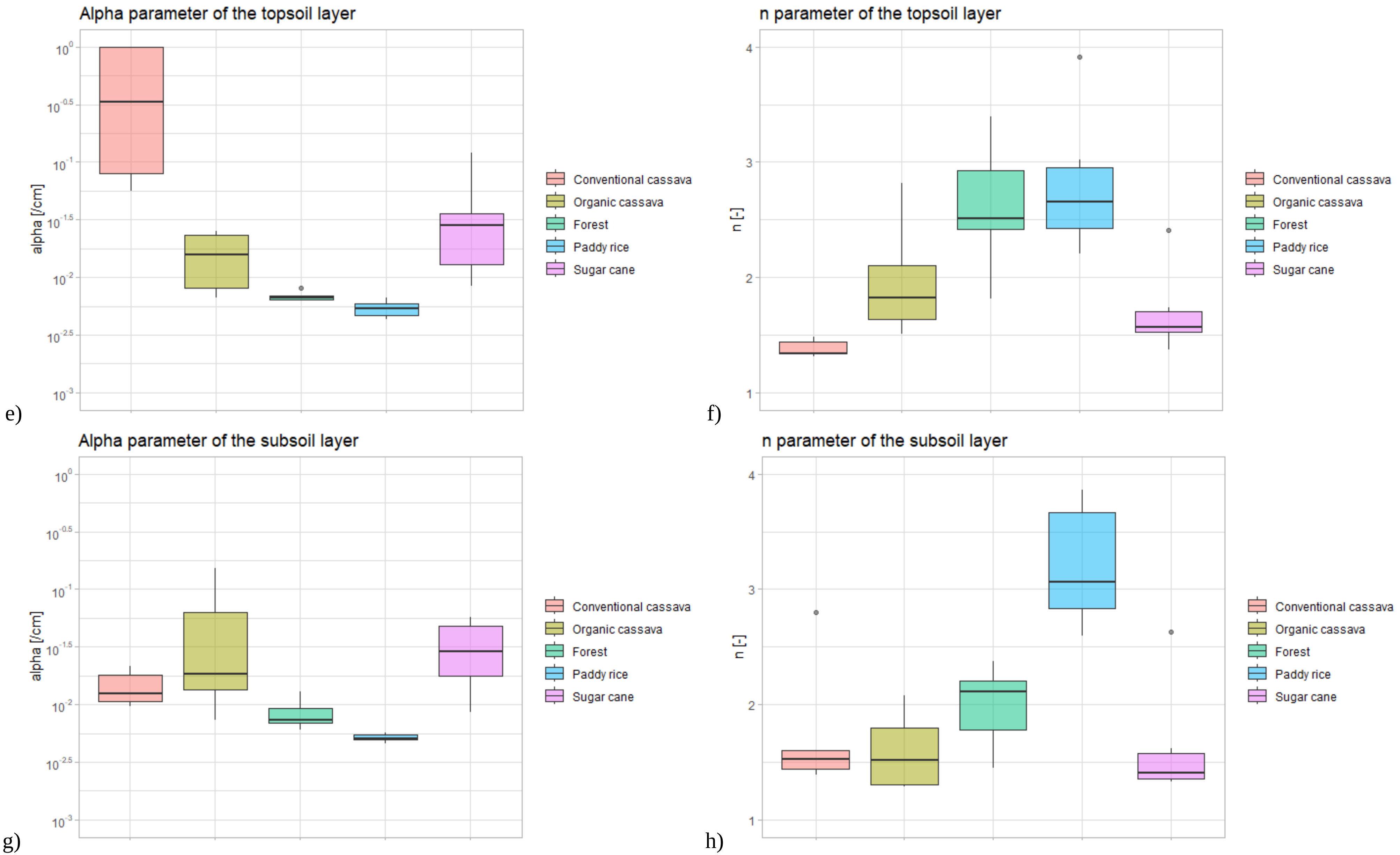


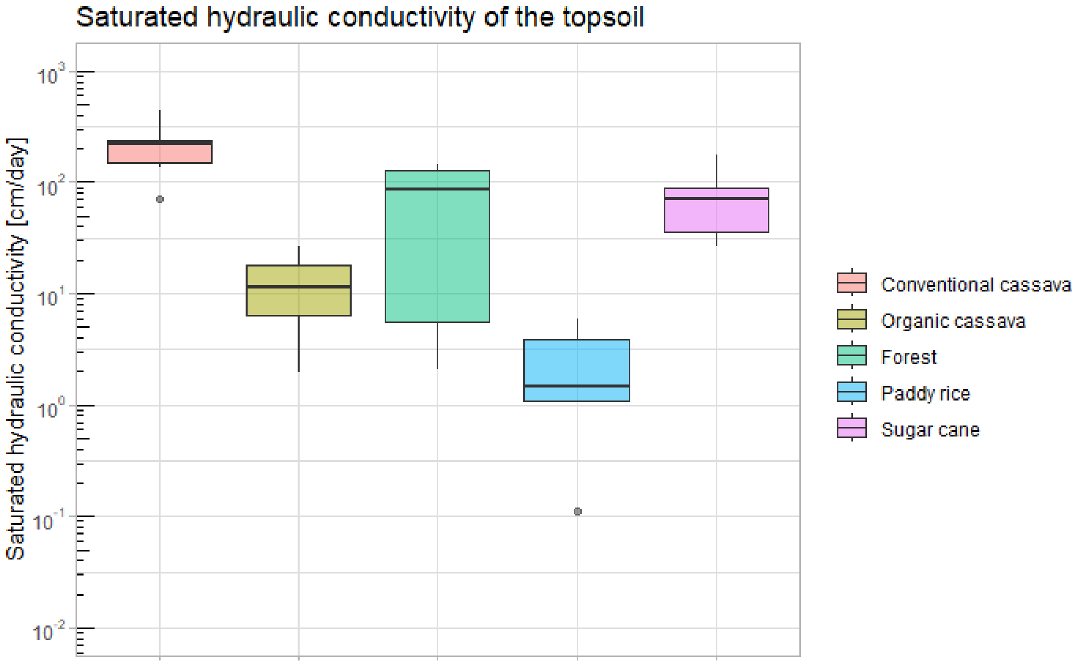
Figure 20 : Alpha parameter (a & c) and n parameter (b & d) of the fitted curves for the topsoil (a & b) and the subsoil (c & d)

e. Hydraulic conductivity

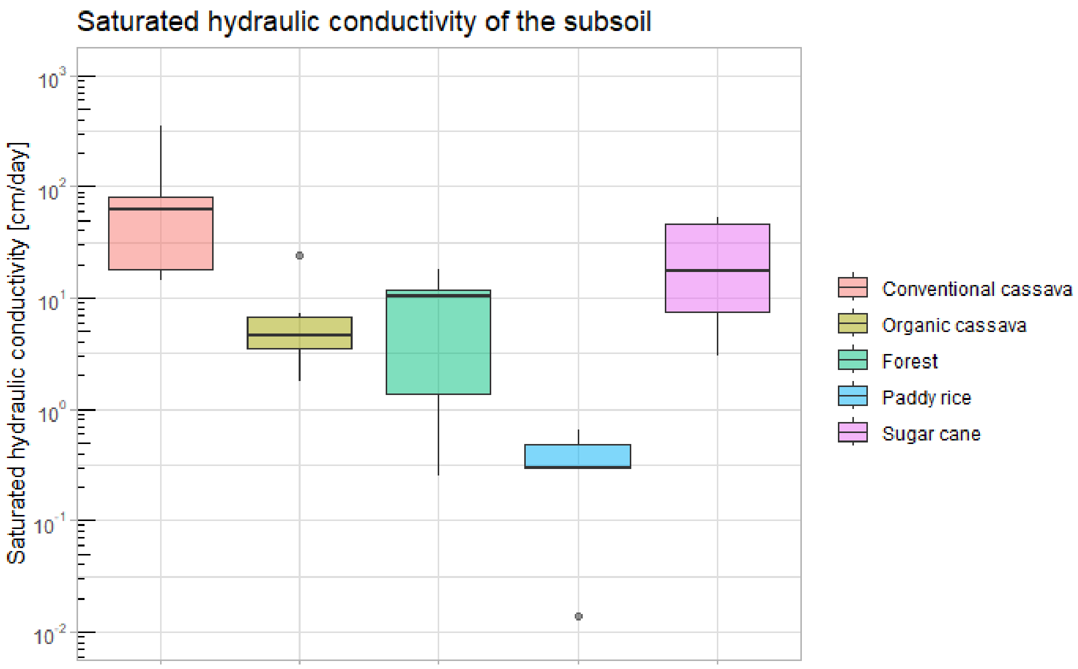
Saturated hydraulic conductivity (K_{sat})

The results are displayed in Figure 21. To run the ANOVA, the variables were transformed logarithmically to pass the Levene Test for the equality of variance. The analysis of the variance presents no interaction between the depth and the land-use but both factors are very highly significant. Thus, the depth influences the saturated hydraulic conductivity by decreasing with increasing depth. Land-use also affects hydraulic conductivity. For the latter, the conductivity related to the conventional cassava is very significantly higher than rest with respective values of 220.72 cm/day and 103.91 cm/day for the topsoil and subsoil. Following the conventional cassava, it is the sugar cane modality with 80.19 cm/day and 26.54 cm/day respectively, before the forest (76.42 cm/day and 8.57 cm/day). Those two modalities are not significantly different from each other. The organic cassava modality, with values 12.89 cm/day and 7.65 cm/day for the topsoil and subsoil, is significantly lower than the conventional cassava and the sugar cane but not significantly from the forest. With the significantly lowest saturated hydraulic conductivity, there is the paddy rice with 2.54 cm/day and 0.35 cm/day for the topsoil and the subsoil respectively.

Increasing depth is often found to be related to decreasing hydraulic conductivity (Garcia & Galang, 2021). Conventional cassava and sugar cane have the highest saturated hydraulic conductivity. It can be related to the coarser soil type of those land-uses (Hillel, 2003; Z. Liu & Wang, 2019; Shwetha & Varija, 2015). The forest's larger interquartile interval of saturated hydraulic conductivity (Figure 21) can be explained by the heterogeneity of root density in this vegetation type (Mair et al., 2022). The difference between cassava and sugar cane is explained by the same reasoning as the fibrous roots of cassava promotes the water flow (Jiang et al., 2018; Shi et al., 2021). The effect of organic management on soil hydraulic properties is not significant but higher values can be observed in organic management (Williams et al., 2017).



a)



b)

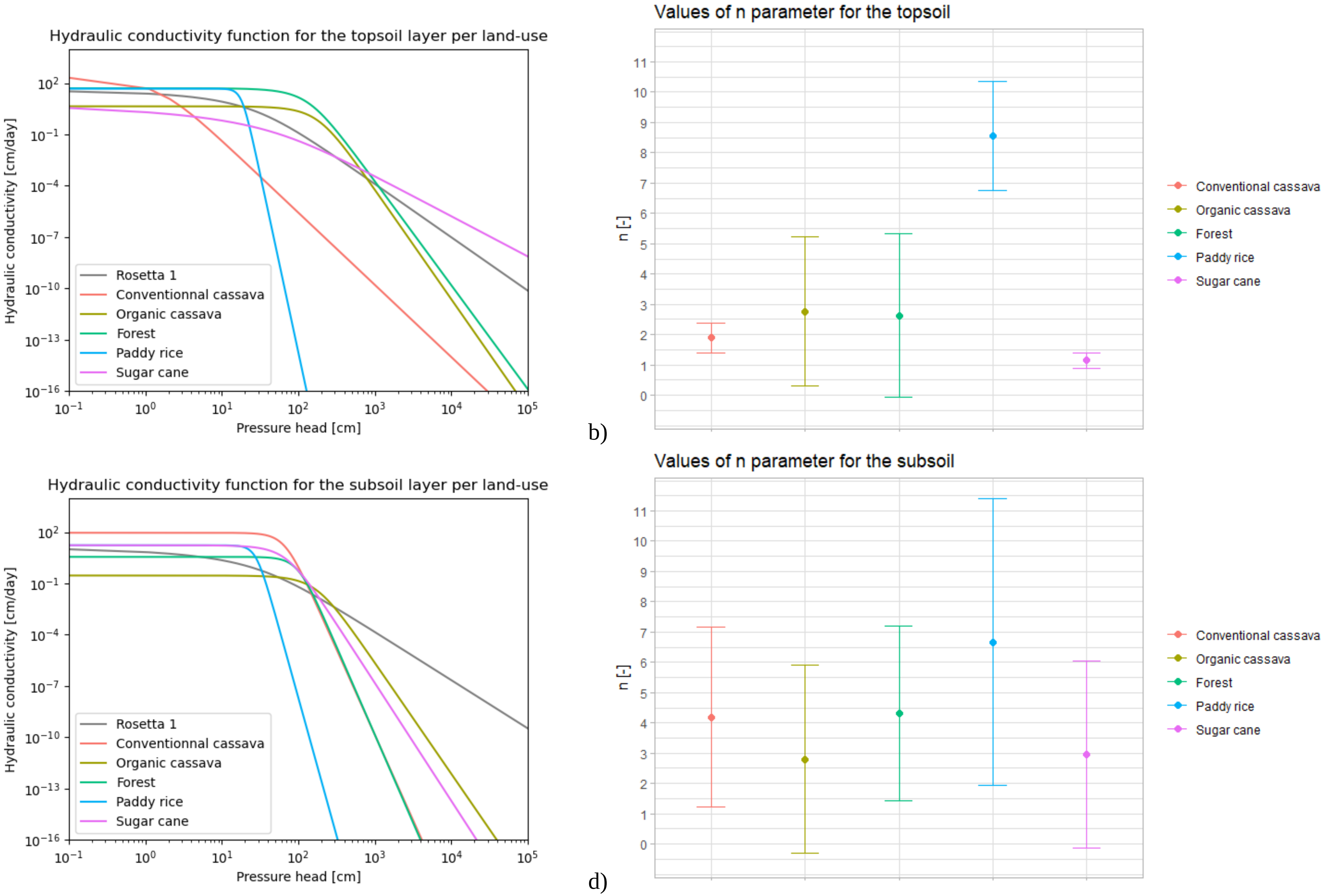
Figure 21 : Saturated hydraulic conductivity of all land-use for a) the topsoil and b) the subsoil

Unsaturated hydraulic conductivity $(K(h))$

The plots for each replicate can be found in the Appendix 10-12.On Figure 22, the hydraulic conductivity function are plotted adjusting the n parameter which is presented on the right of the hydraulic curves. The statistical analysis reveals that the paddy rice modality presents a higher value than the rest of the modalities.

Comparing the tendencies of the curves presented in Figure 12, it can be highlighted that the conventional cassava tends to have a “sand” behaviour on both depths. This modality also presents a higher conductivity at saturation for both depths. As the pressure head decreases and the soil is getting wet, the hydraulic conductivity increases almost linearly until saturation, at pressure equals 0. In the topsoil, the organic cassava and the forest display an gentle slope for the increase in hydraulic conductivity until reaching a plateau around 200 – 300 cm. The sugar cane exhibits a behaviour similar to the sandy-loam texture plotted with the Rosetta 1 parameters. The paddy rice present an steep increase in hydraulic conductivity. For the subsoil, all modalities exhibit sandier trends.

The results need to be observed with caution. Indeed, since only three replicates of one point at a pressure head of 2 cm were taken to fit the whole curves, the real behaviour can not be represented since the hydraulic properties of soil are spatially very disparate (Šípek et al., 2019). The MiniDisk is sensitive to coarse texture (Nestingen et al., 2018) and initial soil water content (Matula et al., 2015). Points at pressure heads of 0.5, 4, 6 and/or 10 cm which are within the range possible of the MiniDisk could improve the data and display the variability of the hydraulic conductivity function.



a)

b)

c)

d)

Figure 22 : Hydraulic conductivity function (a & c) and the corresponding n parameter (b & d) per land-use for the topsoil (a & b) and for the subsoil (c & d).

f. Soil fauna

Soil macrofauna activity

The statistical analysis of the earthworm population highlights that the forest modality is significantly higher than the modalities as shown in Figure 23. Natural environment tends to show greater earthworm populations than agricultural fields (Beare et al., 1997; Iwai et al., 2008, 2010; Iwai & Noller, 2009). The number of earthworms encountered in the agricultural land is low, even for the organic management. This is probably due to the period of sampling and the plot being tilled recently as the cropping season has just begun. Arai et al., (2018) shows that no earthworms were found in arable land after tillage, whether fertiliser were used or not. A few earthworms were spotted in the paddy field as the land was not tilled for the season yet when the experiment was conducted.

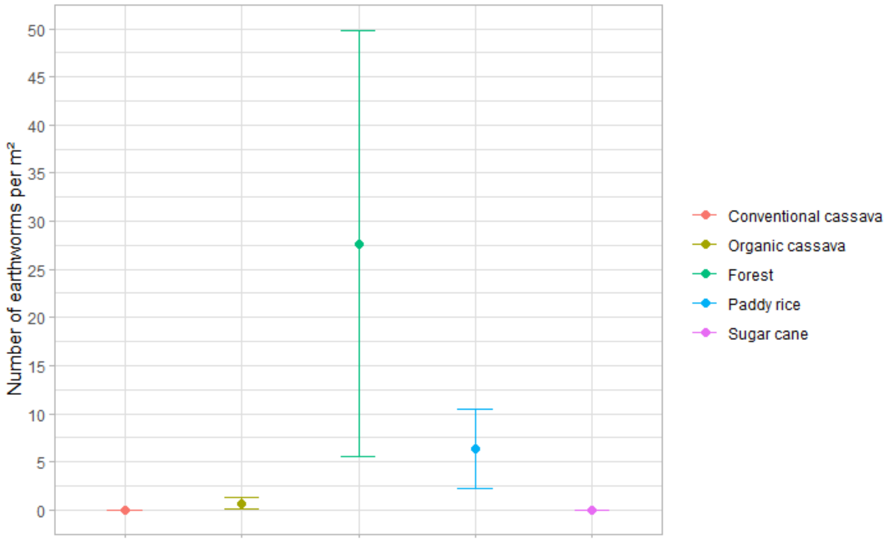


Figure 23 : Mean and standard deviation of the density of earthworms per land-use

The number of cast presents a three distinctive groups : the organic shows the significantly highest count followed by the forest then the three conventionally managed agricultural plots. The presence of casts but the absence of earthworms in the organic cassava is explained by seasonal variability. Indeed, work form Iwai et al. (2010) in the same aera presents a higher number of casts in the dry season than in the rainy season for organic system. The forest environment in the same study scores the highest in the rainy season and falls behind the organic management in the dry season.

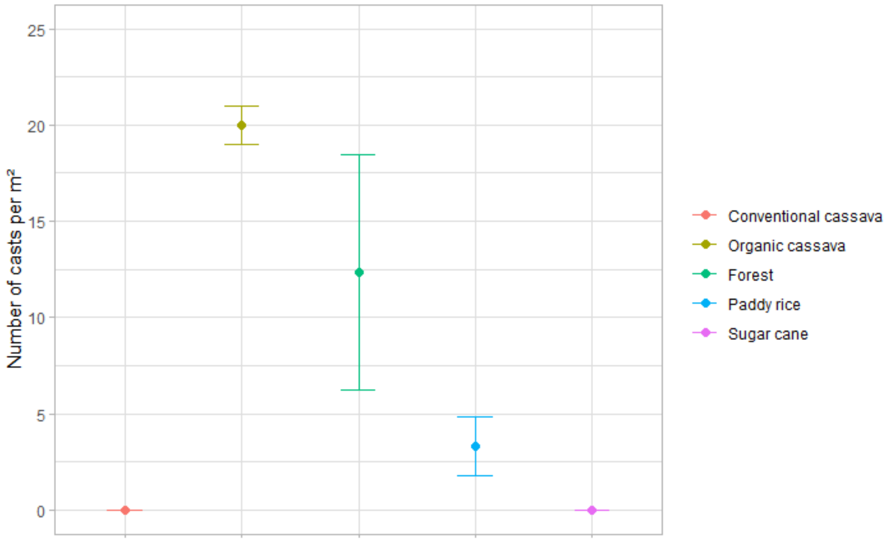


Figure 24 : Mean and standard deviation of the density of casts per m² per land-use

Soil microbial activity

For the soil microbial activity (Figure 25), the variance analysis does not highlight any significant particularity. Soil respiration is sensitive to soil temperature and soil moisture. As the climate in the studied area is classified as a tropical savannah, soil respiration is limited by the high temperature and depend on rainfall to increase the soil moisture. In those types of climate, the soil biota tend to have a low and steady respiration throughout the dry periods and a rapid metabolism when rain occurs (Lyngdoh & Karmakar, 2018; Vallotton et al., 2023). In this case, the rainy season has started but only a few rainfall occurred. Therefore, there are low soil respiration values. The forest presents an outlier at around 180 mg CO_2.kg of soil^{-1}.day^{-1}. This may be caused by manipulation error or due to the natural state of this land-use. Indeed, natural soils present higher variability than agricultural ones as the management make the conditions of the soil more homogeneous. This high value of the forest can also be due to its capacity to keep moisture content longer, thanks to its vegetation cover, than agricultural land and, therefore keeping the activity of the microfauna up. Usually, the organic management shows a higher soil respiration (Araújo et al., 2009; Iwai et al., 2010) but this may depend on the soil conditions during the experiment as organic fertilizers such as manure can slightly increase the soil respiration on the long term (Vallotton et al., 2023).

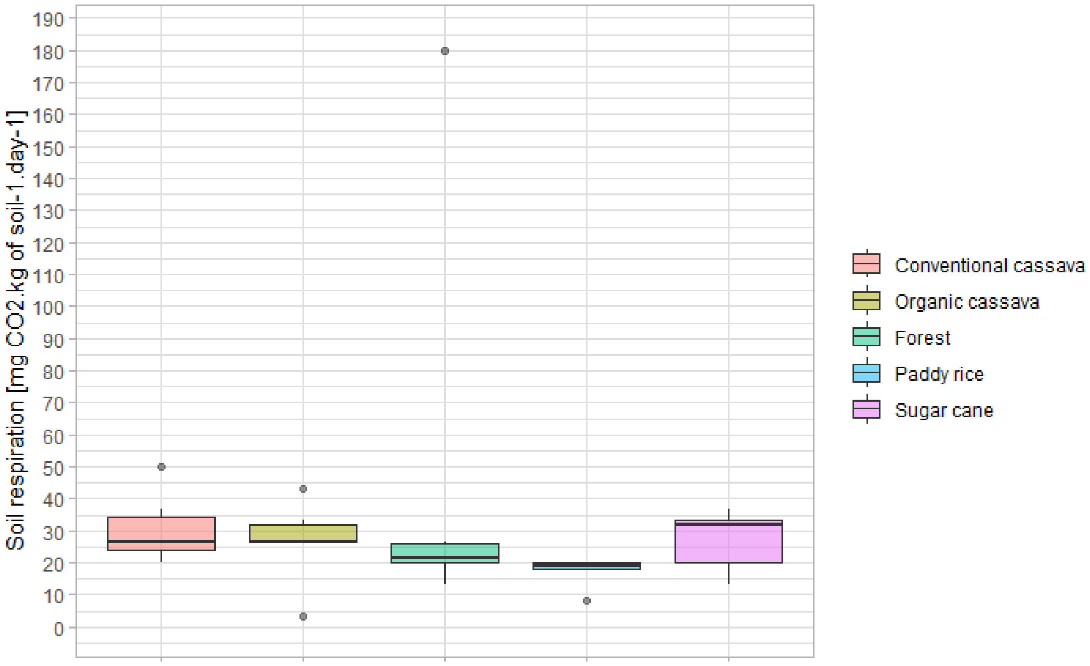


Figure 25 : Soil microbial respiration per land-use.

g. Correlation

The principal component analysis is described through three dimensions, explaining 62.82 % of the total inertia of the dataset. Table 1 shows the correlation between the variables and the dimensions of the PCA. For the first dimension (31.36 % of the variability), water content from the two campaign, the residual water content θ_r of both depth, the saturated water content of the subsoil θ_s, the population of earthworms are opposed to the bulk density and the saturated hydraulic conductivity. For the second dimension (21.66 % of the variability), the soil water content of the first campaign of both depth and the topsoil saturated water content θ_s are on the same side as the bulk density with which are again opposed to the biological parameters. The third dimension opposed the saturated hydraulic conductivity, the residual water content, the subsoil saturated water content and the soil respiration to the topsoil bulk density and the topsoil saturated water content.

The graphs of the variables are displayed in Figure 26 a), Figure 27 c) and Figure 28 e). The same relationships mentioned above can be observed. On the plot of the first two components (Figure 26 a)), an opposed dynamic is highlighted between on one hand, biological parameters, the earthworm populations and the number casts, and on the other hand, the bulk density. The saturated hydraulic conductivity of the topsoil is also opposed to the soil water content of the subsoil and to the earthworms population. In this graph, the saturated hydraulic conductivity is positively related to the bulk density whereas in the second plot of the variables (Figure 27 c)), an opposite relationship is highlighted. In the same plot, the bulk density is negatively related to the soil water content again as well as the saturated hydraulic conductivity. On the last plot (Figure 28 e)), the opposition of the biological parameters to the bulk density and the soil water content is displayed.

The plots of the individuals are displayed in Figure 26 b), Figure 27 d) and Figure 28 f). The ellipses represent where a new point of each modality would be found with a confidence of 50%. From the first graph (Figure 26 b)), it can be. It can be observed that the conventional cassava and sugar cane are close or overlapping on each plots. This means that they have similar behaviour, especially for the significant variables of the corresponding components whereas the other modalities are expected to have a distinct behaviour. On the second plot (Figure 27 d)), the organic cassava is overlapping the sugar cane which is close to the conventional cassava and on the third graph (Figure 28 f)), the conventional cassava and sugar cane are overlapping with each other again and their ellipses take some paddy rice individuals in their ellipse.

Table 1 : Names of the variables and their correlation to the dimensions of the PCA

**** : p-value < 0.001, very highly significant ; ** : p-value < 0.01, highly significant ; * : p-value < 0.05, significant ; shades of red indicate a positive correlation ; shades of blue indicate a negative correlation*

Factor	**Name**	**Dimension 1**	**Dimension 2**	**Dimension 3**
theta_r_T	Residual water content of the topsoil layer	0.730***	-0.119	0.156
theta_s_T	Saturated water content of the topsoil layer	0.132	0.544**	0.441*
alpha_T	The inverse of the air entry suction of the topsoil layer	-0.441*	0.454*	0.536**
n_T	The pore-size distribution of the topsoil layer	0.775***	-0.191	-0.095
Ksat_T	The saturated hydraulic conductivity of the topsoil layer	-0.545**	0.315	0.625**
sw1_T	Soil water content of of the topsoil layer for the first sampling campaign	0.798***	0.417*	-0.046
sw2_T	Soil water content of the topsoil layer for the second sampling campaign	0.724***	-0.066	0.109
bd1_T	Bulk density of the topsoil layer for the first sampling campaign	-0.660***	0.235	-0.423*
bd2_T	Bulk density of the topsoil layer for the second campaign	-0.332	0.565**	-0.433*
pop_ew	Population of earthworms	0.494**	-0.620***	0.125
count_cast	Number of earthworms casts	0.228	-0.859***	-0.036
SR	Soil respiration	0.001	-0.356	0.420*
theta_r_S	Residual water content of the subsoil layer	0.553**	0.109	0.478**
theta_s_S	Saturated water content of the subsoil layer	0.708***	-0.071	-0.445*
alpha_S	The inverse of the air entry suction of the subsoil layer	-0.369*	-0.290	-0.498**
n_S	The pore-size distribution of the subsoil layer	0.773***	0.432*	0.138
Ksat_S	The saturated hydraulic conductivity of the subsoil layer	-0.444*	0.200	0.263
sw1_S	Soil water content of of the subsoil layer for the first sampling campaign	0.688***	0.572***	-0.217
sw2_S	Soil water content of the subsoil layer for the second sampling campaign	0.900***	0.234	0.007
bd1_S	Bulk density of the subsoil layer for the first sampling campaign	-0.062	0.692***	-0.348
bd2_S	Bulk density of the subsoil layer for the second campaign	0.283	0.605***	-0.150

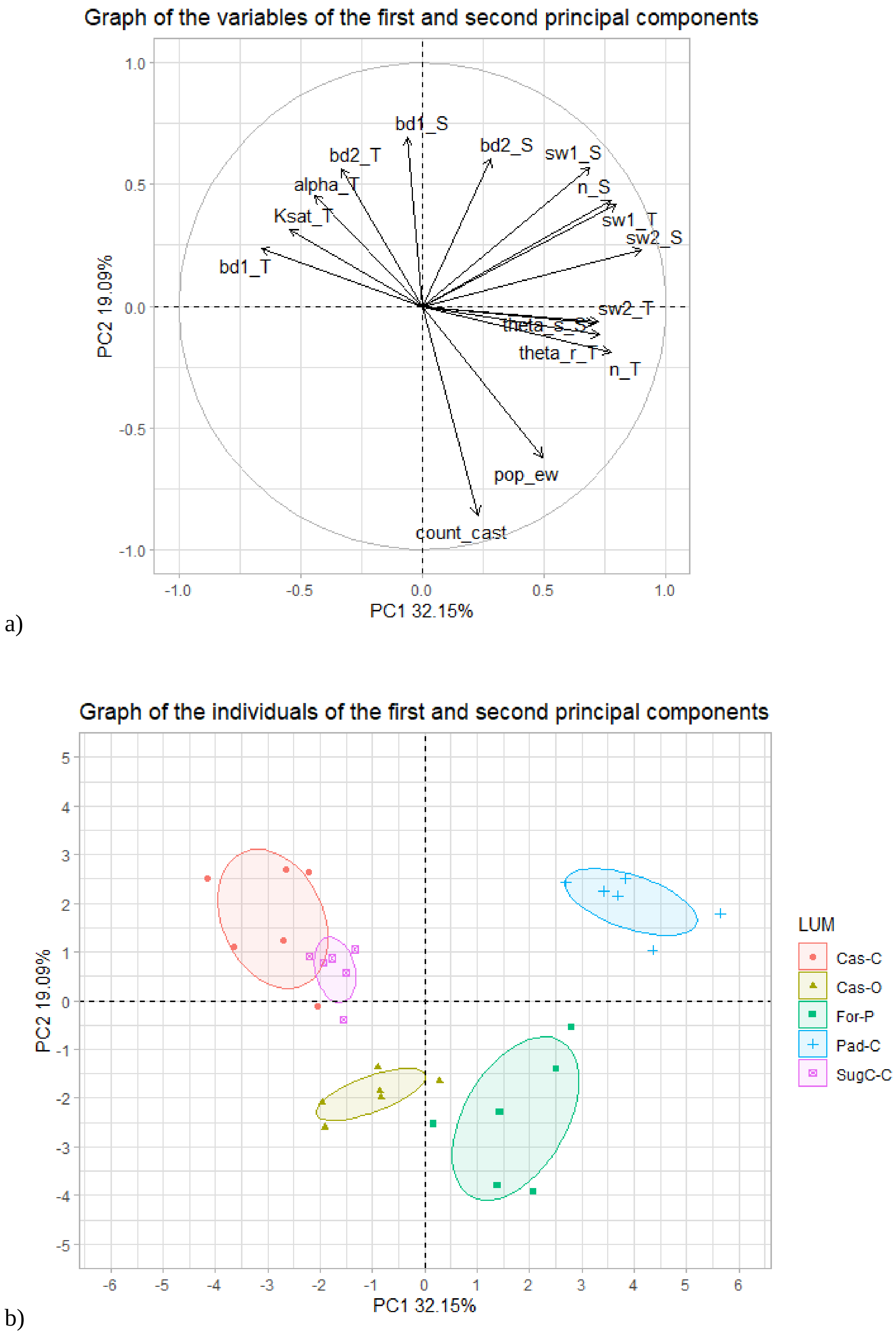


Figure 26 : Plots of the variables (a) and the individuals (b) on the first and second dimensions.
Cas-C : Conventional cassva ; Cas-O : organic cassava ; For-P : forest ; Pad-C : paddy rice ; SugC-C : sugar cane

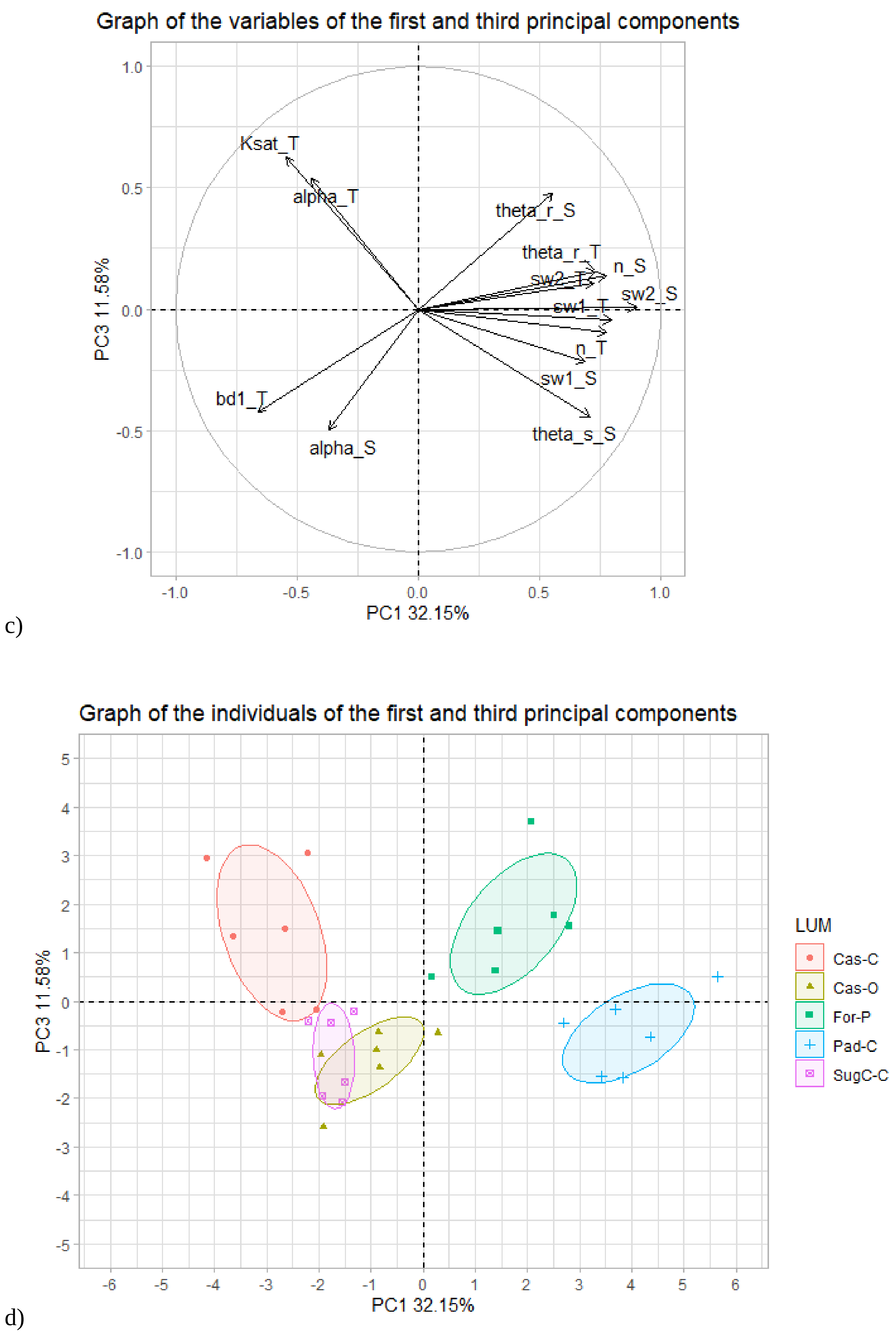
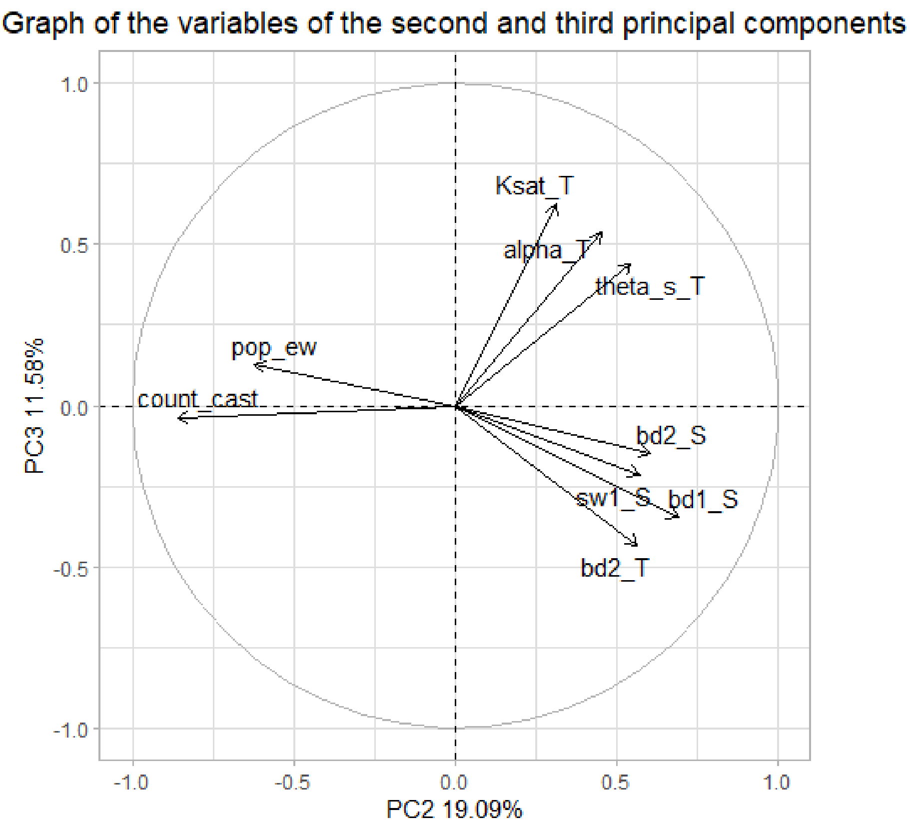
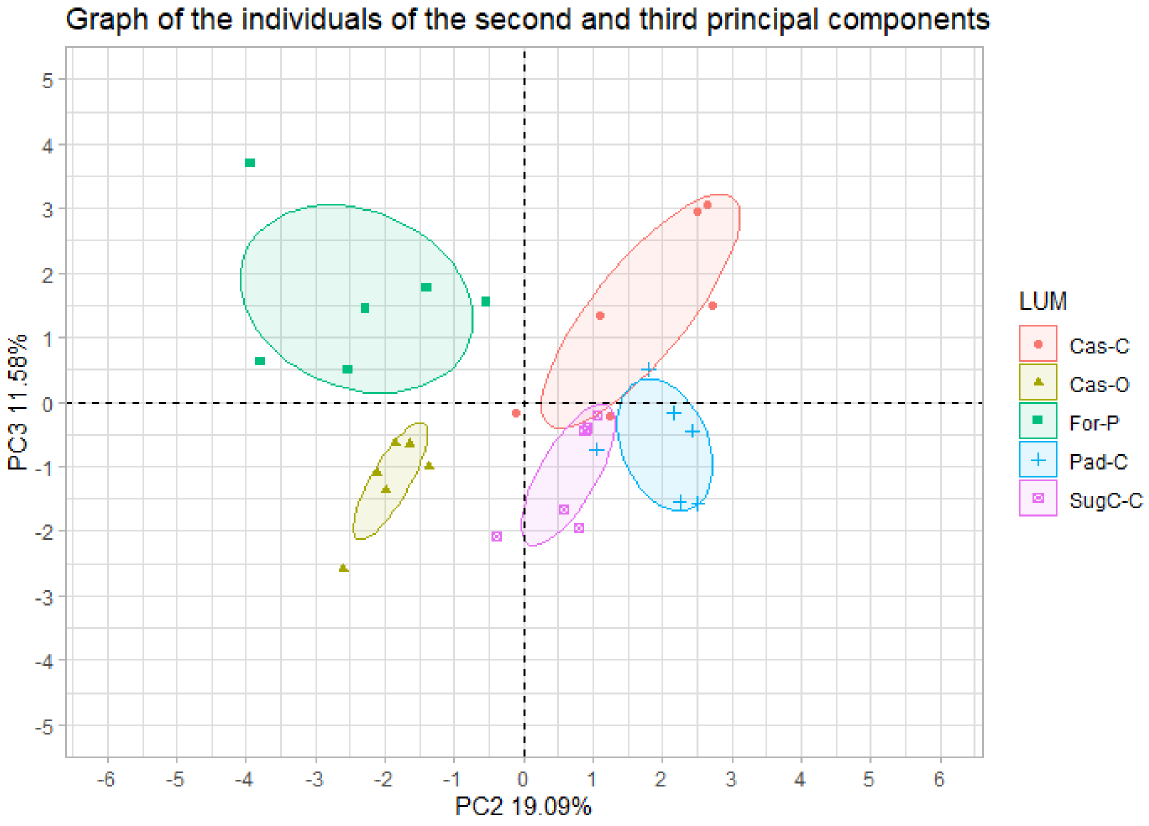


Figure 27 : Plots of the variables (c) and the individuals (d) on the first and third dimensions.
Cas-C : Conventional cassva ; Cas-O : organic cassava ; For-P : forest ; Pad-C : paddy rice ; SugC-C : sugar cane



e)



f)

Figure 28 : Plots of the variables (e) and the individuals (f) on the the second and the third dimensions. Cas-C : Conventional cassva ; Cas-O : organic cassava ; For-P : forest ; Pad-C : paddy rice ; SugC-C : sugar cane

V. Discussion

Errors & variability

Those results must taken cautiously since some data were lost and results are based on estimations (see Data loss). Another point of attention is the working conditions during which the experiments were made. Indeed, the laboratory work done in Thailand was undertaken with average daily temperature ranging from 27.1 °C to 36.1 °C and maximum temperature recorded temperature of 41.6 °C. With those high temperatures, fans and air conditioners were sometimes running which could induce a bias. Indeed, with high temperature, water viscosity decreases whereas matric potential and volume of entrapped air increase (Gao & Shao, 2015; S. A. Grant, 2005; S. Grant & Bachmann, 2002).

Finally, the representative volume elements (RVE) of the samples can be questioned. Li & Sitnikova (2018) describe the RVE as “a volume of the material of a size large enough so that any volume of an increased size will be equally representative”. Although less in agricultural fields as management homogenizes it, the soil’s properties are highly variable through spatiality (Kim, 2009; Šípek et al., 2019; Vallotton et al., 2023). Therefore, the samples collected in kopeckies with height and diameter of around 5 cm can not represent the whole plot even if six replicates at least per physical parameter were assessed. Indeed, as expressed especially in the forest, studies showed that the variability either on physical soil properties as mentioned above or biological properties is important (Alaoui et al., 2011; Cotecchia et al., 2019; Hayashi et al., 2009; Kartini et al., 2023). Earthworms are soil engineers that change the soil porosity and therefore influence the soil’s properties. As the abundance varies in space and time, the soil properties varies along (Schneider et al., 2018). Due to their size, macrofauna may influence larger volume than the 100 cm^3 of the kopeckies whereas nematodes and microarthropods induced localized changes (Snyder & Callaham, 2019). Time dependency plays also an important role, especially under climate with such distinct seasons in rainfall and temperature (Garcia-Montiel et al., 2008; Naik & Pekkat, 2022). The representativity of the data can also not be extrapolated to every land-use on the soil specific soil type as all the samples were collected from one plot of each land-use. Usually, at least three different plots per modality are studied.

Interactions between variables

A relation highlighted in all the components of the PCA is the opposition between bulk density and the biological parameters : soil respiration and numbers of earthworms and casts. This is explained by the influence of bulk density on the porosity. Indeed, Erktan et al. (2020) explained that the soil physical parameters constrain the soil fauna as it influences its habitat. B. Liu et al. (2023) highlighted that a variation in bulk density from 1.30 g/cm^3 to 1.70 g/cm^3 reduces macroporosity from 23.38% to 0.01%. As the mesofauna of the soil, nematodes, collembolans and mites, lives in those pores, their reduction make it impossible for them to settle there (Erktan et al., 2020; Görres & Amador, 2021). Earthworms populations are also influenced by compaction as well as the bacteria (Nawaz et al., 2013), although earthworms can modify their habitat and therefore decrease bulk density by burrowing in the soil (Alegre et al., 1996; Indoria et al., 2020)

In the first dimension of the PCA, bulk density is related to the hydraulic conductivity but in the third dimension, the opposite relation is highlighted. This is confusing and unexpected as bulk density decreases soil porosity (Indoria et al., 2020; Soil Science Society of America, 2008) and therefore could decrease hydraulic conductivity (Aliku et al., 2023; Bhattacharyya et al., 2006; B. Liu et al., 2023). However, water infiltration is more related to the number of macropores and the connectivity between them than actually the porosity changes (Nawaz et al., 2013). B. Liu et al. (2023) demonstrated that over bulk density of 1.50 g/cm³, the saturated hydraulic conductivity is stabilized. Therefore, the relation highlighted between both variables can be due to this as the bulk density is over this limit for all land-uses except the forest. In the Mechanical Soil Database (Schroeder et al., 2022), results demonstrate that sandy soils are capable of high saturated hydraulic conductivity and high density thanks to the specific pore size distribution of those soils.

In every dimension, relation between the residual and saturated water content, two of the estimated parameters of the soil water retention curve, and bulk density are displayed. However, those parameters are correlated positively and negatively depending on the observed dimension. The change in soil water retention curve is noted two ways. From 0 to -10 kPa, increase in bulk density decreases of water content whereas an increase is noted in the range of -250 to -1550 kPa (Alaoui et al., 2011). Ngo-Cong et al. (2021) showed an significant impact of compaction on the water content near saturation (near 0 kPa) which would translate as a decrease in saturated water content parameter. The trend observed for the residual water content would be to increase with bulk density as an increase is noted in low potential matric range but B. Liu et al. (2023) also presented a decrease in residual water content.

Another relation highlighted between the estimated Van Genuchten parameters is the opposition of residual water content and saturated hydraulic conductivity. As the first represents the water content at very low matric potential in the micropores (Fashi et al., 2016) and the saturated hydraulic conductivity is based on the macropores structure(Nawaz et al., 2013), pore size distribution with high density of macropores are expected to present high saturated hydraulic conductivity and low residual water content and reversely.

Saturated hydraulic conductivity is opposed to earthworms populations but correlated to soil respiration. The first relation can be due to the fact that high saturated hydraulic conductivity expressed good drainage conditions which means the water is less retained in the topsoil. Therefore earthworms need to go deeper in the soil to find appropriate living conditions and are not accounted during the field experiment. However, studies show that earthworms increased soil hydraulic conductivity by burrowing the soil (Cheik et al., 2019; Pham Van et al., 2023). The positive correlation between the soil respiration and the hydraulic conductivity is also against what literature would say as the soil activity depends on soil water content to develop in climate like tropical savannah (Vallotton et al., 2023).

Analysis of land-uses

Looking at the data through the land-uses, the conventional cassava is characterized by a texture with more sand. The bulk density in the topsoil is among the highest recorded whereas the subsoil bulk density is in the middle the registered values. This land-use presents a high saturated hydraulic conductivity. For the soil water retention curve, the residual water content is low and the saturated value content is high. No earthworms are detected on that plot. The organic cassava presents high bulk density in the topsoil and in the lower ones of the subsoil. Its saturated hydraulic conductivity is also in the low values, this is probably due to its finer texture found on the field. Regarding Van Genuchten’s parameters, the residual water content is low whereas the saturated water content is low for the topsoil and high for the subsoil. The number of earthworms recorded is low but the number of casts is high. For the forest, the bulk density presents the lowest values and the saturated hydraulic conductivity is middle but higher in the topsoil than in the subsoil. The water retention curve is determined by a high residual water content and a middle saturated content in the topsoil and a low one in the subsoil. The population of earthworms was the highest although the number of cast was lower. This modality also exhibits large spatial variability The paddy rice is characterized by a high subsoil bulk density and a slightly lower bulk density in the topsoil. The saturated hydraulic conductivity is very low and the estimated saturated and residual water contents are both high in both depths. There are a few casts and earthworms. The sugar cane presents the highest bulk densities in both topsoil and subsoil. The saturated hydraulic conductivity is middle. No soil fauna was found and the parameters of the soil retention curve are both low.

The conventional cassava and sugar cane are both located in the sandy soil of the uplands where the water is not near the surface and present high bulk densities. This indicates the presence of compaction, especially in the subsoil that may reduce the yield of the crops and their ability to respond to hydric stress (Smith et al., 2005). A positive impact due to the soil type and compaction can be the increase of the soil's ability to retain water (Brar et al., 2014; FAO & ITPS, 2005). Those soils present a low capacity of water retention as observed in the soil water retention curve as they are both under the others.

Regarding the management of the paddy rice, a lot could be improved to reduce soil compaction, such as : not letting the buffaloes graze on the field, nor working the soil when it is wet. But due to the adventitious roots system of the rice and the soil type, bulk density of 1.2 – 1.3 g/cm³ in the 0-30 cm layer is recommended along with a plough pan of 1.6 – 1.7 g/cm³ (Z. Liu & Wang, 2019).

Impact of organic management

The difference between the management of the cassava are expressed through differences in bulk densities and saturated hydraulic conductivity. The organic management presents soil fauna activity whereas none was detected in the conventional. The overuse of inorganic fertilizer is a threat to soil health. It results in soil contamination and even threats to human health (Aliku et al., 2023). The impact of pesticides and herbicides use is also affecting water and therefore contaminates aquaculture farm (Komarova et al., 2015). Their efficiency could be achieved through useful advices to farmer rather than uniform recommendations provided in Thailand (Haefele et al., 2006). Literature says that recent conversion to organic management does not have an impact on bulk density, soil water retention or saturated hydraulic (Morvan et al., 2018) but does improve the soil stability with larger aggregates (Aliku et al., 2023; Papadopoulos et al., 2014; Williams et al., 2017) therefore prevent soil compaction (Hamza & Anderson, 2005) and limits runoff and erosion (Morvan et al., 2018). Other studies show that this management does have an impact as it improves soil water retention and porosity (Aliku et al., 2023; Gopinath et al., 2023; Mujdeci et al., 2019; Suja et al., 2017). The organic management enhances good structural conditions with increased organic content (Aliku et al., 2023; Papadopoulos et al., 2014). Roots crops with organic fertilizer works well as demonstrated by Seena Radhakrishnan et al., (2022) with cassava. Production of cassava in organic management results in higher income and less energy consumption. With taro, another root crop, the yield on farm is increased by 29% (Suja et al., 2017). Organic management is proven to improve nutritional quality of the crops as well as the average production. Higher soil organic carbon and nitrogen is also displayed (Gopinath et al., 2023).

Parameters to estimate soil compaction

Even if soil compaction is defined through bulk density, there are others indexes. Among those, there are the S index represented by the slope of the soil water retention curve or the degree of compactness (DC) which is the ratio of the field dry bulk density and the reference bulk density of this soil. The latter bulk density can either be obtained through the Hakansson method or using a Proctor. Both are good indicator of the soil physical quality but the compactness degree is easier to obtain (Naderi-Boldaji & Keller, 2016). However as proven in this study and mentioned in the Introduction, the soil compaction affects physical, chemical and biological properties of the soil (Batey, 2009). Therefore, the estimation of the overall soil quality is requested. Soil indexes are based on 1) physical and chemical parameters 2) biological indicators 3) functional approaches.

For the first category, the relevant physical indicators are bulk density (de Paul Obade & Lal, 2016; Heepngoen et al., 2021; Z. Liu & Wang, 2019), available water content (de Paul Obade & Lal, 2016; Heepngoen et al., 2021; Pulido Moncada et al., 2014), pH (Heepngoen et al., 2021; Z. Liu & Wang, 2019), saturated hydraulic conductivity, especially for tropical soils (Z. Liu & Wang, 2019; Pulido Moncada et al., 2014), soil texture (de Paul Obade & Lal, 2016; Z. Liu & Wang, 2019). Regarding the chemical parameters, carbon content is assessed through soil carbon content (de Paul Obade & Lal, 2016; Pulido Moncada et al., 2014), total carbon (Heepngoen et al., 2021) or organic matter analysis (Z. Liu & Wang, 2019). Other chemical properties studied are total nitrogen, available phosphorus and potassium and exchangeable calcium (Heepngoen et al., 2021; Z. Liu & Wang, 2019).

Biological indicators shows high potential and are faster to obtained than other analysis (Bünemann et al., 2018; Muon et al., 2022; Tarafdar, 2022). A commonly used indicator is based on the nematodes populations as those species influence the food web of the soil (Erktan et al., 2020; Heepngoen et al., 2021).

Functional approaches are described here using the Biofunctool® methodology. Three soil functions are studied. Carbon transformation in the soil is based on turnover of carbon pool and soil organisms activity which is assessed through cast density measurement, Lamina baits test and soil basal respiration (Heepngoen et al., 2021; Thoumazeau et al., 2019). The second soil function is nutrient cycling measured through available nitrogen and nitrates dynamics. The last function studied is the structure maintenance of the soil with measurements of the aggregates stability, the infiltration and a visual assessment of the horizons structure (Heepngoen et al., 2021; Thoumazeau et al., 2019).

Taking into account the means to estimate soil quality presented above, the physico-chemical approach neglects the biology of the soil. Although, soil fauna highly influences soil dynamics. The biological estimators are promising but can be costly and require some expertise. Lastly, estimation of soil quality through functional approach are sensitive to soil degradation, easy to implement and do not need expertise but the soil processes are not indicated. Another issue comes from the recent development of this type method resulting in a need of database information to score soil quality (Bünemann et al., 2018; Heepngoen et al., 2021; Thoumazeau et al., 2019).

Enhancing food security

In order to ensure food supply for the exponentially growing populations, agriculture practices and land-uses management must be sustainable. Agricultural sustainability can be acquired through several practices such as organic fertilization, as mentioned above, crop rotation, crop covers, no-tillage or reduced tillage. The implement of those systems can also be challenging for farmers.

The cropping system can be optimized through crop diversification, crop rotation and intercropping. Crop diversification is the concept of growing more than one crop per plot at the same time. This improves production but also enhances biodiversity and nutrients use while reducing pathogens (Yang et al., 2020). On the other hand, crop rotation implies rotation of the crop type cultivated on the plot. This concept increases yield through bettering of soil health and repressing pests by breaking its life cycle (Yang et al., 2020). The efficiency of this system relies on the type of crop used in the rotation as demonstrated by several studies on rice (Goulart et al., 2020; Hossain et al., 2021).

Tillage has effects on soil physical and biological parameters. Indeed, as presented in the results, it annihilates earthworms from agricultural plots (Arai et al., 2018; Arora et al., 2022). Therefore conventional tillage reduces soil macrofauna whereas no-tillage systems present higher population (Arai et al., 2018). No-tillage management lowers bulk density, raises carbon content and aggregates in soil as well as the pore connectivity. All of this impacts water content of the soil (Arai et al., 2018; da Luz et al., 2020; Pires et al., 2017). However, no-tillage management must be monitored as this may induce soil compaction (da Luz et al., 2019). The short-term production of this system can not be guaranteed either and it usually takes four to five years to observe an increase in yield (Aliku et al., 2023; Godwin et al., 2022). In Thailand, implementations of such management by farmers is done by a ‘preference-risk calculus” as they take account of labour required, financial results and risks among other parameters (Amekawa, 2013).

The adoption of such practices and the risk it may take slow down the process. The proof that this system can work in Thailand is brought by the implementation of zero tillage conservation agriculture (ZT/CA) in Brazil. Farmers agronomists and researchers work together to develop and implement on it more than 50% of annual crop system of the country. The adoption of this system happened after unsuccessful attempts to mitigate soil erosion. This ZT/CA system even allows cultivation in the low productivity regions of the Cerrados savannah (de Freitas & Landers, 2014).

VI. Perspectives

Although data retrieval has been successful, additional analysis of the studied parameters is worth considering to enhance the interactions between parameters mentioned above. Exploring a minimum of three other plots presenting the same attributes could determine the accuracy of the mentioned results while mitigating the impact of the geographical factor. Pending the farmer's consent, pits on the field could be dug to assess the variability in depth. Expanding the size of the undisturbed soil sample to obtain the representative element volume of each soil would be challenging as 1) soil is a highly heterogenous media, 2) the size of manufactured rings is limited. Increasing the number of observations per plot is viable but would increase the sampling duration. Temporal impact could be assessed by taking samples at the beginning, during and at the end of the monsoon season.

To enhance the accuracy of the hydraulic curve, additional suction values such as other suction values such 0.5, 6 or 10 cm could be measured. Regarding the saturated hydraulic conductivity, employing a plexiglass pipe could effectively keep the water above the sample consistently to assure device reusability of the constant-head.

The chemical quality of the soil was not assessed in this study but investigation of the interaction of soil biology and carbon sequestration is currently undertaken by Praew Yara from Khon Kaen University. Concerning potential subjects, studying the impact on soil of various tillage management, such conventional, reduced and no-tillage, could be interesting. Additionally, how different crop systems and nutrient management influence the soil quality in tropical climate is also a critical question. Finally, cost-benefits analysis of various management against conventional management could help farmers to feel more incline to adopt such practices and guide resource allocation.

VII. Conclusion

To conclude, this study provides valuable insights on the complex interactions between various parameters describing soil compaction and impacting soil quality. Despite the challenge encountered with data loss, the results present foundation to understand the intricate relationships between physical and biological parameters of the soil.

A cautious approach is imperative when interpreting the findings due to the presence of errors and inherent variability. The influence of high laboratory temperatures on experimental outcomes underscores the necessity of accounting for potential biases caused by temperature fluctuations. Moreover, the limitations associated with representative volume elements highlight the need for more accurate sampling strategies that capture the variability of soil properties through seasons and space.

The intriguing associations between bulk density, saturated hydraulic conductivity and biological parameters highlight the multiplicity of soil parameters interactions. This relationships challenge usual assumptions and point out the need for tailored strategies to assess soil health. The distinctive impacts of land-use and management emphasize the requirement of specific agricultural practices depending on soil and climate.

As population continues to grow, ensuring food security becomes imperative. Sustainable agricultural practices, including crop diversification, rotation, and no-till farming, offer promising solutions to enhance production while mitigating environmental impacts. Collaboration between farmers, researchers, and agronomists will be crucial for successful implementation and adaptation of such practices in diverse contexts.

To sum up, this study not only sheds light on the complex dynamics within soil systems but also underscores the importance of global approaches to sustainable agriculture. While acknowledging limitations and complexities, it highlights the need for interdisciplinary research, adaptive management strategies, and a comprehensive understanding of soil interactions to address the challenges of food security and environmental sustainability in the years to come.

VIII. Personal contribution

The student was actively engaged in all phases of the project. She conducted extensive literature research to gain a comprehensive understanding of soil compaction, especially in the context of northeastern Thailand. She selected sampling points in the field, drafted protocols, and carried out laboratory experiments. The student also processed and interpreted the obtained results, developed the code for generating the presented graphs, presented the results and engaged in critical discussions. After informatic mishandling, she also demonstrated abilities to find a way to estimate missing results, which allows to carry out the study as initially planned. Estimated results were discussed with the appropriate caution.

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Appendices

Land-use (management)	Topsoil		Subsoil		Difference between topsoil and subsoil
	Mean	Standard deviation	Mean	Standard deviation	
Cassava (C)	1.52	0.07	1.61	0.09	+ 0,09
Cassava (O)	1.49	0.05	1.52	0.04	+ 0,03
Forest	1.26	0.16	1.49	0.07	+ 0,23
Paddy rice	1.38	0.17	1.66	0.10	+ 0,28
Sugar cane	1.52	0.05	1.69	0.05	+ 0,17

Appendix 1 : Mean and standard deviation of the bulk density for the topsoil and the subsoil of the first sampling campaign

Land-use (management)	Topsoil		Subsoil		Difference between topsoil and subsoil
	Mean	Standard deviation	Mean	Standard deviation	
Cassava (C)	1.57	0.05	1.67	0.06	+ 0.10
Cassava (O)	1.55	0.04	1.57	0.04	+ 0.02
Forest	1.19	0.15	1.67	0.16	+ 0.48
Paddy rice	1.53	0.15	1.78	0.07	+ 0.25
Sugar cane	1.55	0.06	1.82	0.04	+ 0.27

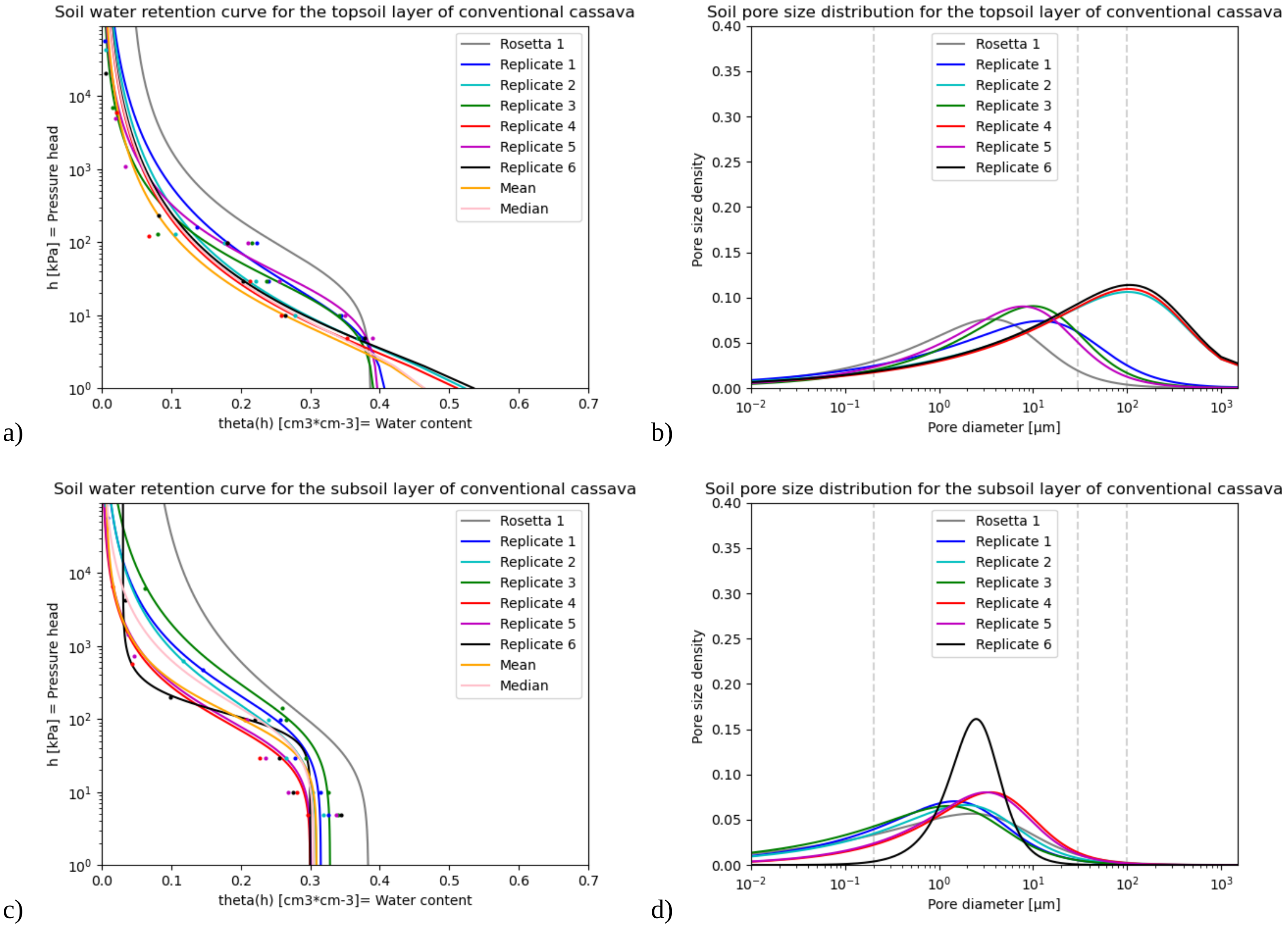
Appendix 2 : Mean and standard deviation of the bulk densities [g/cm³] of the topsoil and subsoil of all land-uses of the second sampling campaign

Land-use (management)	Topsoil		Subsoil		Difference between topsoil and subsoil
	Mean	Standard deviation	Mean	Standard deviation	
Cassava (C)	0.26	0.03	0.31	0.01	+ 0.05
Cassava (O)	0.34	0.03	0.31	0.01	- 0.03
Forest	0.38	0.09	0.36	0.03	- 0.02
Paddy rice	0.41	0.09	0.40	0.02	- 0.01
Sugar cane	0.27	0.02	0.34	0.01	+ 0.07

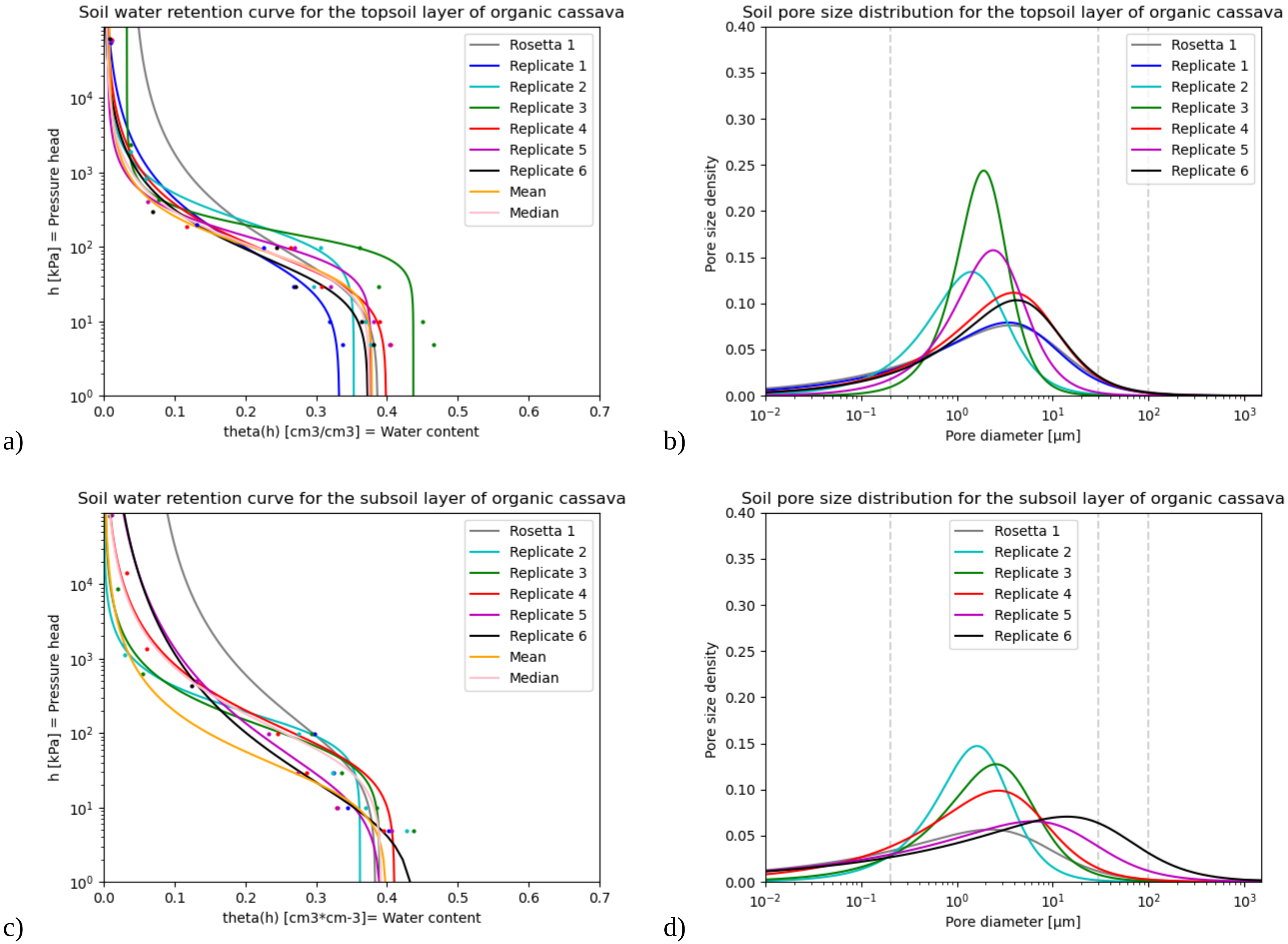
Appendix 3 : Mean and standard deviation of the volumetric water content [cm³/cm³] of the topsoil and subsoil of all land-uses of the second sampling campaign

Land-use (management)	Topsoil		Subsoil		Difference between topsoil and subsoil
	Mean	Standard deviation	Mean	Standard deviation	
Cassava (C)	220.72	124.47	86.70	130.14	- 134.02
Cassava (O)	12.89	9.31	7.65	8.19	- 5.24
Forest	76.42	62.57	8.57	6.90	- 67.85
Paddy rice	2.54	2.40	0.28	0.20	- 2.26
Sugar cane	80.19	60.46	26.53	23.11	- 53.66

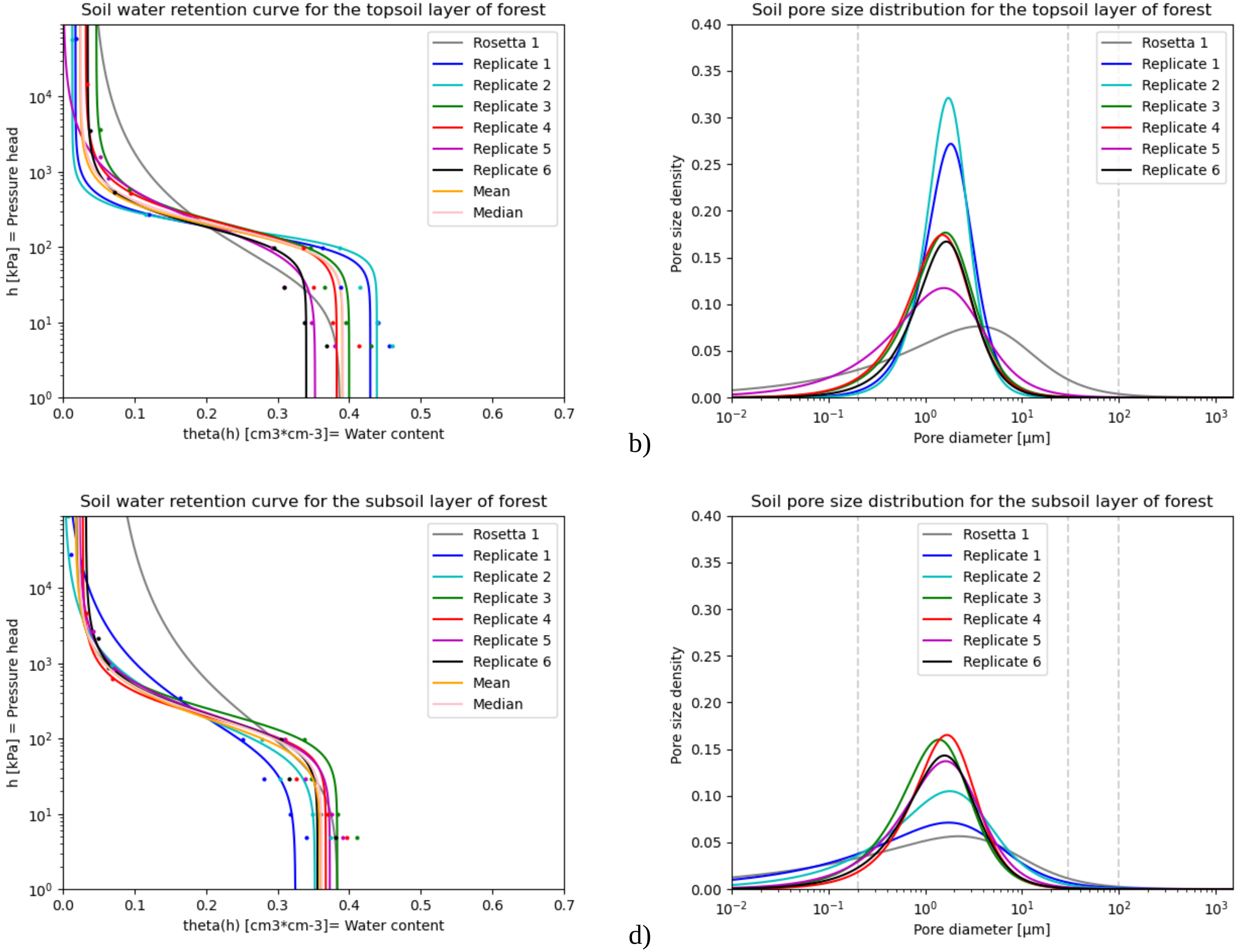
Appendix 4 : Mean and standard deviation of the saturated hydraulic conductivity [cm/day] of the topsoil and subsoil of all land-uses



Appendix 5 : Soil water retention curve of the conventional cassava a) for the topsoil, c) for the subsoil and their corresponding pore size distribution c) for the topsoil d) for the subsoil. The Rosetta 1 curve uses the Van Genuchten parameters based on the soil type mentioned on the soil map. The grey dotted lines divide the pore classes : macropores with diameter > 150 µm and mesopores with diameter between 150 µm and 30 µm which represent the drainage pores ; micropores < 30 µm which is divided in two hydraulic classes : > 0.2 µm are the storage pores and < 0.2µm are the residual pores.



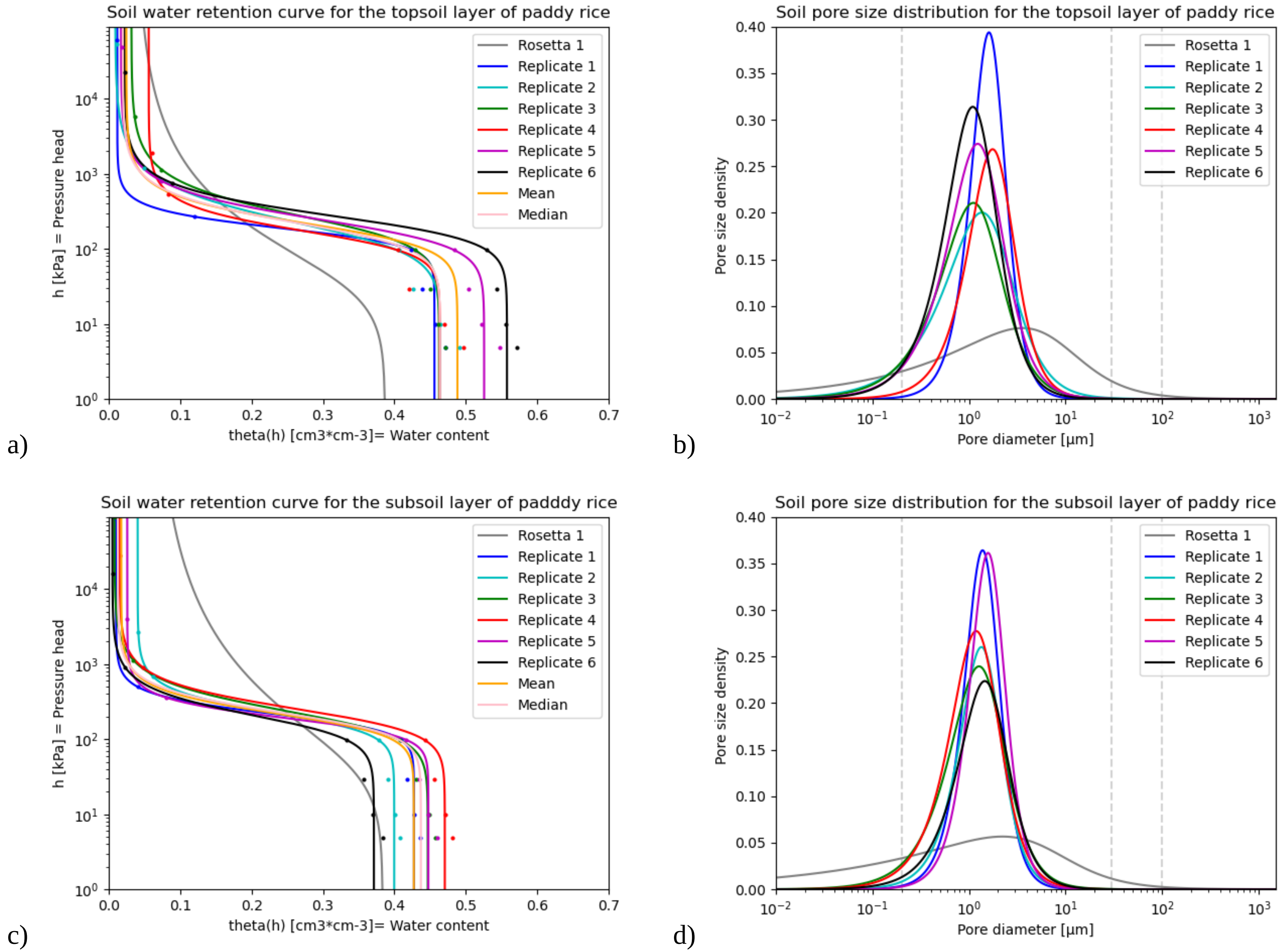
Appendix 6 : Soil water retention curve of the organic cassava a) for the topsoil, c) for the subsoil and their corresponding pore size distribution c) for the topsoil d) for the subsoil. The Rosetta 1 curve uses the Van Genuchten parameters based on the soil type mentioned on the soil map. The grey dotted lines divide the pore classes : macropores with diameter > 150 µm and mesopores with diameter between 150 µm and 30 µm which represent the drainage pores ; micropores < 30 µm which is divided in two hydraulic classes : > 0.2 µm are the storage pores and < 0.2µm are the residual pores.



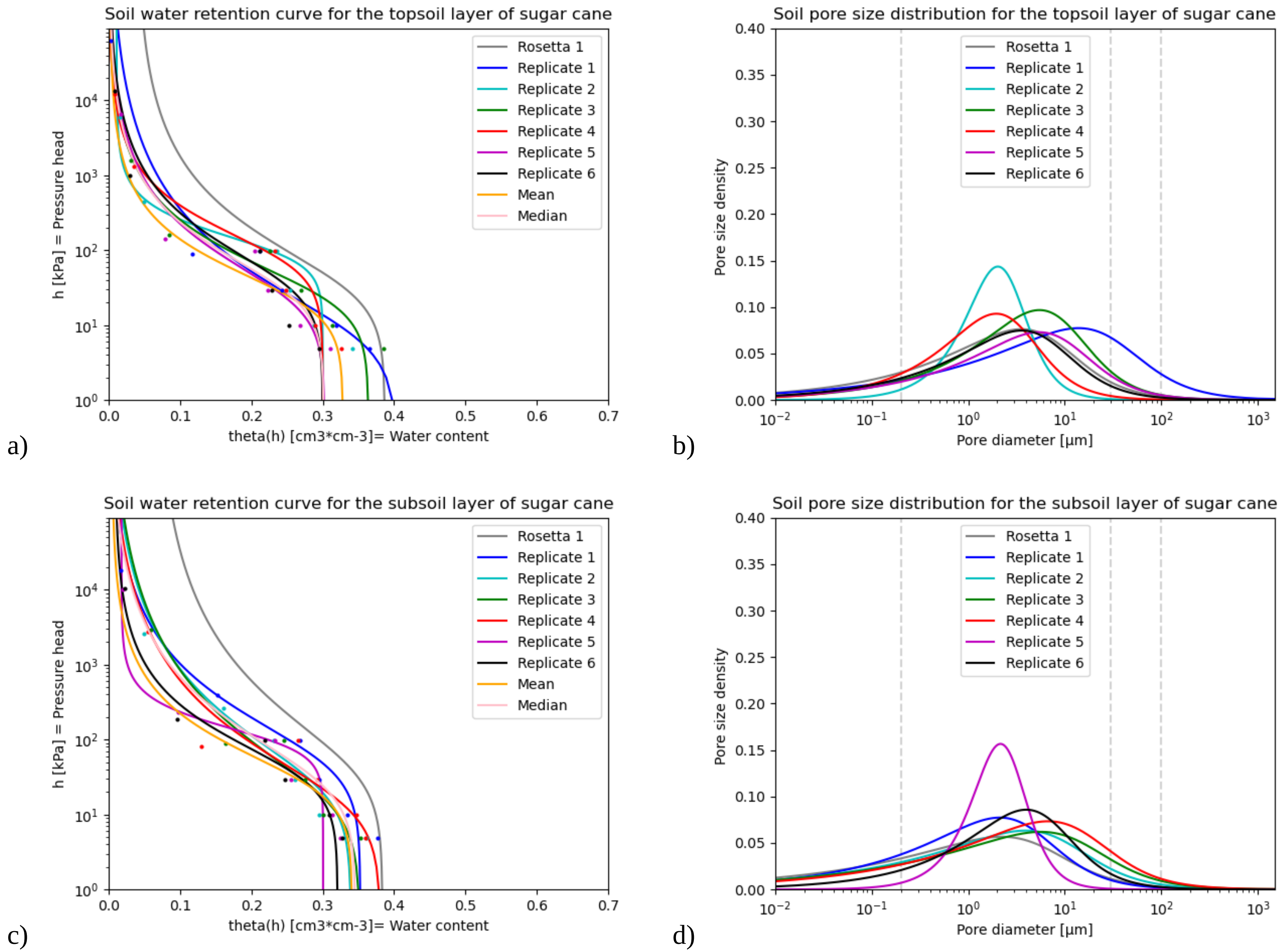
a) b)

c) d)

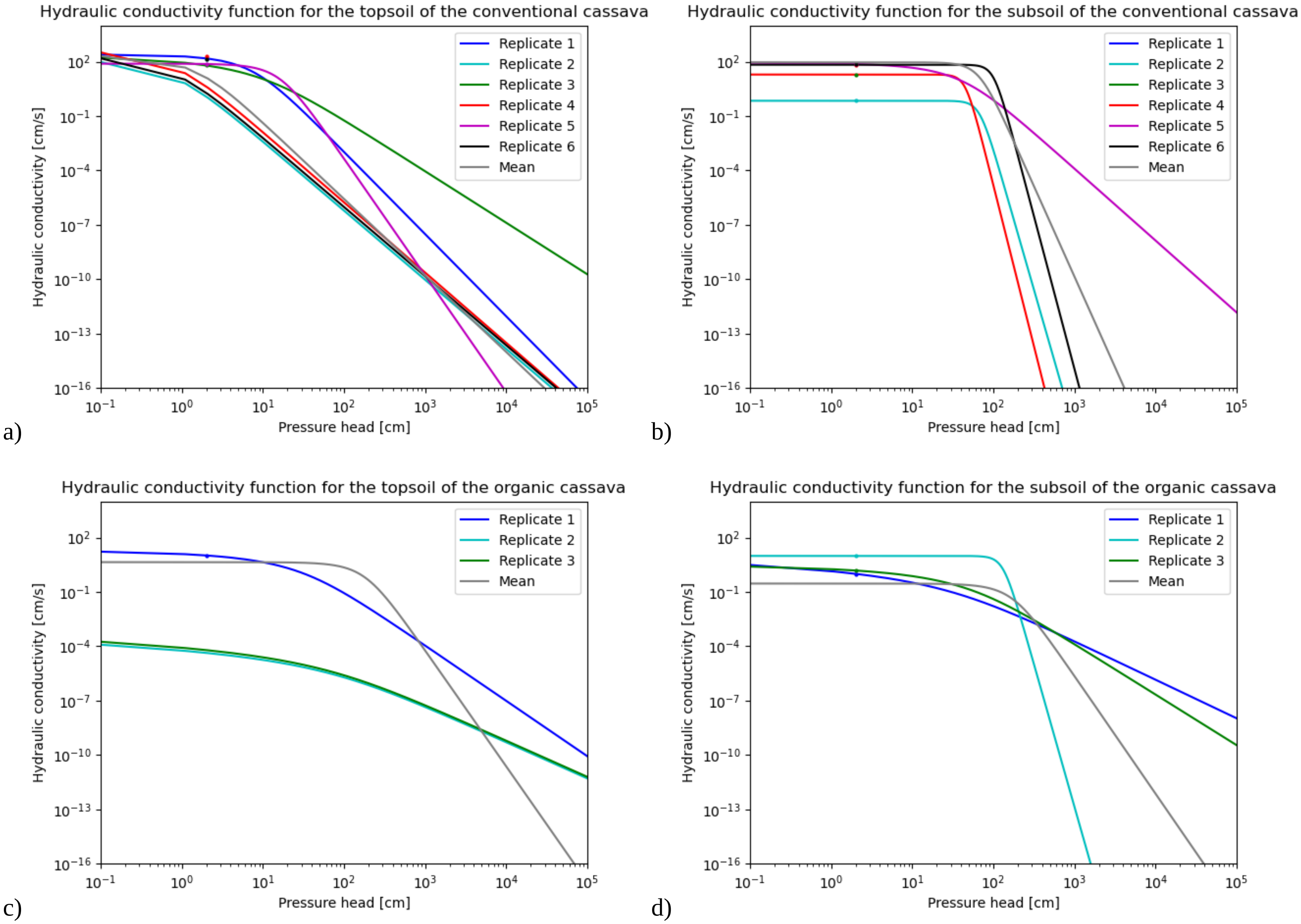
Appendix 7 : Soil water retention curve of the forest a) for the topsoil, c) for the subsoil and their corresponding pore size distribution c) for the topsoil d) for the subsoil. The Rosetta 1 curve uses the Van Genuchten parameters based on the soil type mentioned on the soil map. The grey dotted lines divide the pore classes : macropores with diameter > 150 µm and mesopores with diameter between 150 µm and 30 µm which represent the drainage pores ; micropores < 30 µm which is divided in two hydraulic classes : > 0.2 µm are the storage pores and < 0.2µm are the residual pores.



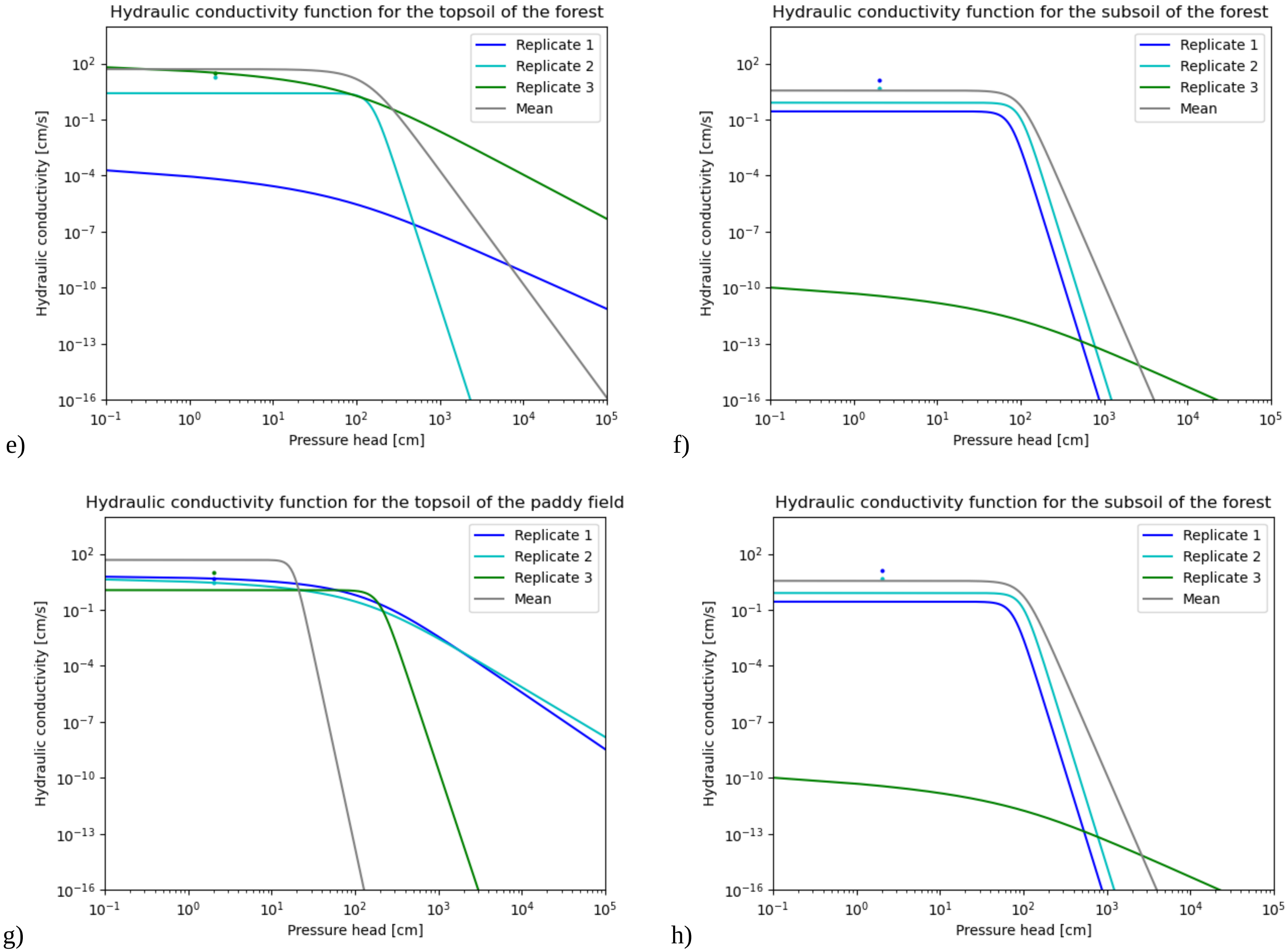
Appendix 8 : Soil water retention curve of the paddy rice a) for the topsoil, c) for the subsoil and their corresponding pore size distribution c) for the topsoil d) for the subsoil. The Rosetta 1 curve uses the Van Genuchten parameters based on the soil type mentioned on the soil map. The grey dotted lines divide the pore classes : macropores with diameter > 150 µm and mesopores with diameter between 150 µm and 30 µm which represent the drainage pores ; micropores < 30 µm which is divided in two hydraulic classes : > 0.2 µm are the storage pores and < 0.2µm are the residual pores.



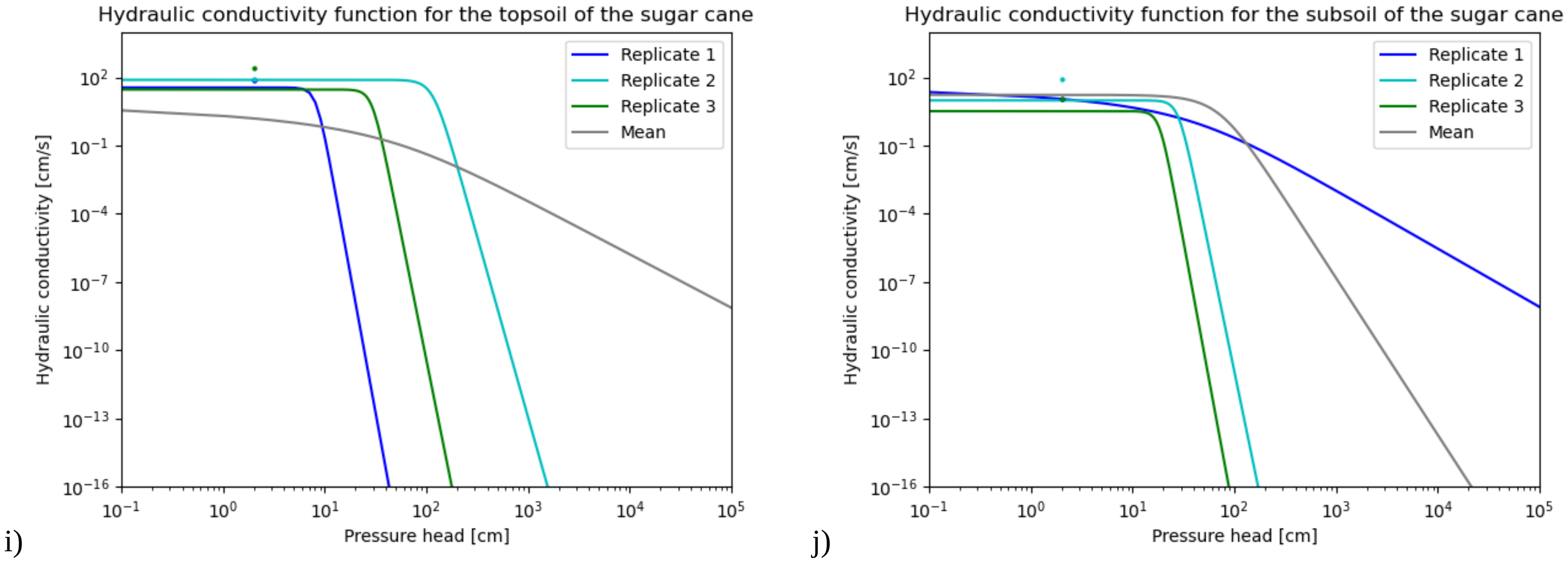
Appendix 9 : Soil water retention curve of the sugar cane a) for the topsoil, c) for the subsoil and their corresponding pore size distribution c) for the topsoil d) for the subsoil. The Rosetta 1 curve uses the Van Genuchten parameters based on the soil type mentioned on the soil map. The grey dotted lines divide the pore classes : macropores with diameter > 150 µm and mesopores with diameter between 150 µm and 30 µm which represent the drainage pores ; micropores < 30 µm which is divided in two hydraulic classes : > 0.2 µm are the storage pores and < 0.2µm are the residual pores.



Appendix 10 : Hydraulic conductivity curve of the conventional (a & b) and the organic (c & d) cassava of the topsoil and subsoil respectively



Appendix 11 : Hydraulic conductivity curve of the forest (e & f) and the paddy rice (g & h) of the topsoil and subsoil respectively



Appendix 12 : Hydraulic conductivity curve of the sugar cane of the topsoil and subsoil respectively