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CARBON SEQUESTRATION UNDER DIFFERENT LAND USES AND SOILS IN THE STATE OF QUINTANA ROO, MEXICO

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CONTENTS

ABSTRACT

Rising in global temperature is evidently related to atmospheric carbon dioxide (CO_2) and methane (CH_4) concentrations; this has become an environmental problem. The use of renewable energy, the development of eco-friendly merchandise and the enforcement of biomass management have been proposed to mitigate the issue. In the ecosphere, the pedosphere stores 1,500 to 2,500 PgC, which is four times more than the carbon stored in biomass; hence, it is very important to carry out soil carbon studies because of more long-term stability of such storage. In the study, soil carbon quantification was applied to the entire state of Quintana Roo, using a purpose oriented sampling, to observe the dynamic between land uses and soils, relating all relevant characteristics and properties of the landscape. To study the carbon content stored in soils, total carbon was estimated through loss-on-ignition, organic carbon by Walkley-Black method and inorganic carbon by calcium carbonate determination. The result portrays that the coastal dune vegetation-Arenosol (1,256 Mg C ha^{-1}) is the combination with the highest soil carbon density, while Leptosol is the soil type with the highest storage capacity (852 MtC). Consequently, the soil carbon storage not only relates to soil properties but also associates with the surface area occupied by the specific soil type. In addition, the characteristics of the landscape play an important role in the storage of soil carbon. Due to that, soil carbon storage can be explained by biogeomorphoedaphic factors.

Key words: soil properties, organic carbon, inorganic carbon

RESUMEN

Evidentemente, el incremento en la temperatura global está relacionado con la concentración de dióxido de carbono (CO_2) y metano (CH_4) en la atmosfera. Esto ya se volvió un problema ambiental. El uso de energía renovable, el desarrollo de mercados eco-amables y el manejo de la biomasa han sido alternativas de mitigación. En la ecosfera, la pedosfera ocupa 1,500 a 2,500 PgC y captura cuatro veces más CO_2 que la biomasa. Debido a la gran estabilidad del almacenamiento de CO_2 a largo plazo en suelo es muy importante llevar a cabo un estudio del carbono (C) almacenado en el suelo. En el presente estudio, se presenta la cuantificación de carbono en suelos del Estado de Quintana Roo, utilizando un muestreo dirigido, con la finalidad de observar la dinámica de los cambios uso de suelo relacionados con las características y propiedades del paisaje. Para estimar la magnitud del almacenamiento, se cuantificó el carbono total con el método de calcinación, se obtuvo el carbono orgánico a través del método de Walkley-Black, y se estimó el carbono inorgánico por la determinación de carbonato de calcio. El resultado muestra que la duna costera-Arenosol (1,256 Mg C ha^{-1}) es la combinación con la mayor densidad del carbono en el suelo por acumulación de materiales exógenos, mientras Leptosol es el suelo que representa la mayor capacidad en el secuestro de carbono (852 MtC). Por lo tanto, el almacenamiento de carbono en el suelo no solo se relaciona con las propiedades del suelo sino también se asocia con la superficie ocupada por el tipo de suelo. Además, las características del paisaje juegan un papel importante en la conservación de los inventarios de carbono en el suelo. Esto indica que, el almacenamiento de carbono en el suelo se puede ser explicado al menos parcialmente por los factores biogeomorfoedáficos del territorio.

Palabras Clave: propiedades de suelo, carbono orgánico, carbono inorgánico

ZUSAMMENFASSUNG

Nach derzeitigen wissenschaftlichen Erkenntnissen stehen die steigenden globalen Temperaturen in ursächlichem Zusammenhang mit den Konzentrationen von Treibhausgasen, insbesondere Kohlendioxid (CO_2) und Methan (CH_4), in der Atmosphäre. Dies ist zu einem großen Umweltproblem geworden. Um das Problem zu mildern, wurden die Nutzung erneuerbarer Energien, die Entwicklung umweltfreundlicher Technologien und Waren und die Implementierung eines Biomasse-Managements vorgeschlagen. In der Ökosphäre speichert die Pedosphäre zwischen 1,500 und 2,500 PgC. Dies ist in etwas viermal so viel wie in dergesamten Biomasse gespeichert wird. Daher ist es sehr wichtig, Studien über den Gehalt von Kohlenstoff im Boden durchzuführen, da dieser eine langfristige Speicherung ermöglicht. In der Studie wurde eine Kohlenstoffquantifizierung für den gesamten mexikanischen Bundesstaat Quintana Roo vorgenommen, wobei mehrere Stichproben verwendet wurden, um die Dynamik zwischen Landnutzungen und Böden zu beobachten, in Verbindung mit allen Merkmalen und Eigenschaften der Landschaft. Um den in den Böden gespeicherten Kohlenstoffgehalt zu untersuchen, wurde der Gesamtkohlenstoff durch das Verfahren der Kalzinierung ermittelt, der Gehalt des organischen Kohlenstoffs wurde mit Hilfe der Walkley-Black-Methode geschätzt, während der Gehalt des anorganischen Kohlenstoffs mit Hilfe der Bestimmung des Calciumcarbonatgehalts festgestellt wurde. Das Ergebnis zeigt, dass Küstendünen-Arenosole (1,256 Mg C ha^{-1}) die höchsten Kohlenstoffdichte besitzen, während Leptosol der Bodentyp mit der höchsten Speicherkapazität für Kohlenstoff (852 MtC) ist. Folglich hängt die Speicherkapazität des Bodens nicht nur von den Bodeneigenschaften ab, sondern auch von der Fläche, auf der dieser Bodentyp zu finden ist. Darüber hinaus spielen die Merkmale der Landschaft eine wichtige Rolle bei der Erhaltung des Vorkommens von Kohlenstoff im Boden. Dadurch kann die Speicherung von Kohlenstoff in den Böden durch biogeomorphoedaphische Faktoren erklärt werden.

Schlüsselwörter: Bodeneigenschaften, organischer Kohlenstoff, anorganischer Kohlenstoff

概要

近年來全球環境問題凸顯，二氧化碳(CO_2)和甲烷(CH_4)的濃度引起了全球溫度上升。因此，再生能源的開發、生態環保商品的使用和生物量管理成為應對這一問題的重要方案。在生態圈中，土壤可儲存一萬五千至二萬五千億噸的碳，比植物多出了四倍，這表明土壤儲量更加長久穩定，所以對土壤碳的研究極為重要。本研究區域位於墨西哥金塔納羅奧州，採用目地性的抽樣方式來觀察與景觀特征和性質相關的動態土地使用與土壤碳存量。通過強熱減量統計 (總土壤碳)，採用了 Walkley-Black (有機碳) 和碳酸鈣 (無機碳) 的測定以研究土壤中儲存的碳含量。結果表明，沿海沙丘和 Arenosol 土壤類型的組合 (1,256 Mg C ha^{-1}) 的碳含量是最高的，Leptosol 土壤類型的碳儲存量能力是最強的 (852 MtC)。因此，土壤碳儲存不僅與土壤性質有關，而且與土壤類型占據的面積有關。此外，景觀特徵在保持與獲取土壤碳中起了重要作用，所以土壤碳儲存可以通過生物、地質、地形與土壤因素來解釋。

關鍵詞：土壤性質，有機碳，無機碳

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LIST OF ACRONYMS AND ABBREVIATIONS

AD	Acid Dissolution Method
AR	Arenosol
BD	Bulk density
BSI	Bare soil index
$CaCO_3$	Calcium carbonate
$CaMg(CO_3)_2$	Dolomite
$CaSiO_3$	Calcium silicate
CDV	Coastal dune vegetation
CH_4	Methane
CM	Cambisol
CNHS-O	Elemental analyzer
CO	Carbon monoxide
CO_2	Carbon dioxide
CR	Rock fragment
Cr_2O_7	Dichromate
CSI	Coastal shrubland
EC	Electrial conductivity
$FeSO_4$	Ferrous sulfate
FL	Fluvisol
FLF	Flooded low rainforest
Gha	Global hectare
GHGs	Greenhouse gases
GL	Gleysol
GTC	Gigatonnes of carbon
H_2CO_3	Carbonic acid
H_2O	Water
H_2SO_4	Sulfuric acid
H_3PO_4	Phosphoric acid
H_4SiO_4	Silicic acid
HCl	Hydrochloric acid
HCO_3	Bicarbonate
HS	Histosol
HWSD	Harmonized World Soil Database
INEGI	National Institute of Statistics and Geography (Mexico)
IP	Induced palm
IPCC	Intergovernmental panel on climate change
$K_2Cr_2O_7$	Potassium dichromate
KS	Kastanozem

LIC	Lithogenic inorganic carbon
LOI	Loss-on-ignition
LP	Leptosol
LV	Luvisol
$MgCO_3$	Magnesium carbonate
N/Id	Unidentified content
NaOH	Sodium hydroxide
NDVI	Normalized difference vegetation index
NEP	Net ecosystem production
NP	Natural palm
NPP	Net primary production
NT	Nitisol
OM	Organic matter
PgC	Petagram carbon
PH	Phaeozem
PIC	Pedological inorganic carbon
ppbv	Parts per billion by volume
ppmv	Parts per million by volume
RG	Regosol
SAGARPA	Secretariat of Agriculture, Livestock, Fisheries and Food (Mexico)
SC	Solonchak
SdLF	Semi-deciduous low rainforest
SdMF	Semi-deciduous medium rainforest
SeHF	Semi-evergreen high rainforest
SeLF	Semi-evergreen low rainforest
SEMARNAT	Secretariat of Environment and Natural Resources (Mexico)
SeMF	Semi-evergreen medium rainforest
SIC	Soil inorganic carbon
SiO_2	Silicon dioxide
SOC	Soil organic carbon
SOCw	Soil organic carbon estimated from Walkley-Black
SOM	Soil organic matter
SRC	Short rotation coppice
TH	Thickness of the soil extracted (soil depth)
TLF	Thorny low rainforest
TSC	Total soil carbon
UNDP	United Nations Development Programme
UQROO	University of Quintana Roo (Mexico)
Vis-NIR	Visible-near infrared
VR	Vertisol
WB	Walkley-Black

INTRODUCTION

Currently, climate change is a topic under discussion because some affirm that it is a natural phenomenon while others say that it is provoked by anthropogenic activities. According to the analysis of temperature oscillation done by Scotese (2002) cited by Moore (2015), the change in temperature and carbon dioxide (CO_2) has been unstable since the Precambrian period until today. However, the change in temperature is a natural phenomenon but it is undeniable that atmospheric greenhouse gases influence the Earth's climate and most probably higher greenhouse gas (GHG) concentrations lead to an increase of global temperatures. Most climate scientists believe that human activities, in particular the burning of fossil fuels and large-scale deforestation, lead to higher GHG concentrations in the atmosphere that in turn lead to higher global temperatures; this process is called anthropogenic climate change.

Indisputably, the content of CO_2 in the atmosphere has increased dramatically along with other GHGs since the industrial revolution. The concentration of CO_2 has risen from 280 ppmv to 367 ppmv between 1750 (preindustrial) and 1999, and continues to increase 1.5 ppmv / year or 3.3 Pg C / year (1 Pg = petagram = billion tonnes) (Martínez and Fernández-Bremauntz, 2004). On the other hand, the concentration of CH_4 has increased from about 700 to 1745 ppbv in the same period and continues to increase to 7 ppbv / yr (Lal, 2004). Recently, the CO_2 is approximately 410 ppmv (Kahn, 2017) and CH_4 is 1807 ppbv (IPCC, 2013), demonstrating an exponential increase in the carbon content. According to SEMARNAT (2009), CO_2 is one of the most important GHGs and its emission into the atmosphere by changes in land use, ranks second place worldwide with a strong contribution to climate change in the tropics. In addition, the annual worldwide deforestation with an estimate of 17 million hectares represents about 20% of the total anthropogenic emissions which is equivalent to an annual release of approximately 1.8 GtC^3 (Arevalo-Madrigal, 2015).

As mentioned above, most carbon emissions are caused by human activities which come from various sources, mostly from combustion of fossil fuels used in power generation, transportation, industrial processes, residential and commercial buildings, etc. If the evaluated sources are distributed worldwide, the database can be classified into four major regions with the highest emissions: North America, Europe, East Asia and South Asia (IPCC, 2005). Specifically, Mexico considered a country of the North American continent produces 1.3% of the global CO_2 emissions, ranking 13th place worldwide. From the total emission of Mexico, 92% comes from the combustion of fossil fuels and the remaining is caused by changes in land use (OCDE, 2013). Nationally, forests are one of the best carbon storage which captures approximately 8 GtC; but lamentably, it is rapidly lost by deforestation and degradation of forest ecosystems (Benjamín and MASERA, 2001). Therefore, the Mexican government pledged to reduce 25% of GHGs by 2030 in the United Nations Climate Change Conference held in 2015.

On Earth, there exist five major types of carbon storage (atmosphere, biosphere, pedosphere, and lithosphere). According to these authors (Odum and Warrett, 2006; Smith and Smith, 2007; U. S. DOE., 2008), carbon transfers from one reservoir to the next during the carbon cycle via the process of photosynthesis (atmosphere to biosphere), respiration (biosphere, pedosphere & hydrosphere to atmosphere), decomposition of matter (biosphere to pedosphere), and human intervention (biosphere & pedosphere to atmosphere). Relating the relocation of carbon to the first law of thermodynamics (Rodriguez, 2009), we can say that the carbon released is neither created nor destroyed; nonetheless, it is just being deposited in a certain carbon reservoir. Since carbon content in the ecosphere remains the same, it is important to keep carbon in the storage which causes no harm to the environment. As mentioned by IPCC (2015), biosphere is usually considered in mitigating the current climate issue through ecosystem management; however, the estimated carbon stock (Lal, 2004; Odum and Warrett, 2006; Smith and Smith, 2007; U. S. DOE., 2008) is lower in comparison with the pedosphere, due to rapid carbon flux (Colomb et al., 2014). Consequently, the more efficient means is in forms of soil carbon.

In Mexico, Quintana Roo is among the states with the greatest diversity of vegetation and soil types. According to the State Program of Action on Climate Change in Quintana Roo done by Pereira-Corona et al. (2013), the State Committee on Climate Change of Quintana Roo was established on 31 August 2010 in order to coordinate national and state policies and actions for the prevention and mitigation of GHG emissions, and also adapt to the effects of climate change. In addition, it proposed a list of mitigation actions, such as reduction of energy consumption, utilization of renewable energies, dissemination of programs through regulations, implementation of environmental technologies, establishment of environmental system management, execution of efficient public transport, forest restoration, diminution of all emissions, and conservation of ecosystems. Therefore, the study of the relationship between vegetation and soil types in the State of Quintana Roo will serve as a reference to link the dynamics of carbon sequestration in the soil with its respective aboveground biomass. It will also assist the implementation of the best environmental system management that is considered as an alternative strategy for mitigating carbon emissions. Therefore, the study aims to estimate organic and inorganic carbon from the combination of soil type and vegetation found throughout the State of Quintana Roo to observe the effects of its characteristics and properties. Moreover, the study not only serves as the first reference for future research but also for governmental decision planning.

HYPOTHESIS

There is a relation between land use and soil types to carbon sequestration due to distinct vegetation characteristics and soil properties.

OBJECTIVES

General Objective

To relate the content of carbon captured in different soil types associated with its respective land uses, vegetation characteristics, soil properties, anthropogenic impacts, climate and geomorphology of the study area.

Specific Objectives

- To identify the distinct soil types and vegetation classes found in the State of Quintana Roo;
- To find the relationship between properties of soils and land uses in relation to soil carbon;
- To describe the geographical distribution of carbon stock in accordance with the landscape of the region.

CHAPTER 1: THEORETICAL FRAMEWORK

1.1 Global Carbon Cycle

Carbon is a basic element of life that constructs the organic compounds and forms part in the chemical storage of energy through photosynthesis. The carbon source comes from living organisms, fossil deposits, CH_4 and CO_2 released into the atmosphere, biomass and water bodies. The carbon flux transposes between the deposits (atmosphere, hydrosphere, biosphere, lithosphere, and pedosphere), thereby forming a carbon cycle that works as a natural recycler of carbon atoms. Biologically, the carbon flux derives from the process of photosynthesis and respiration. The first process is carried out when the plants use solar energy to convert water and CO_2 into carbohydrates. The other process, aerobic respiration occurs in the presence of oxygen, in which the carbohydrate is broken down into water molecules and CO_2. On the other hand, in conditions of oxygen deficiency, the breakdown of the carbon compounds is accomplished by microorganisms, producing CH_4 and CO_2 as end products. However, for a geological process, carbonic acid is slowly formed from the reaction between CO_2 and water (H_2O) but in some conditions, the process is reversed to achieve its equilibrium. Carbonic acid is essentially important for the control of pH levels in the ocean by the release of hydrogen and bicarbonate ions (HCO_3^-). Thanks to the biological characteristic of water, the fixation of HCO_3^- and calcium ions (Ca^{2+}) is made to produce calcium carbonate ($CaCO_3$), which is a substance used by organisms such as corals, crustaceans, some protozoa and algae in the formation of shells and other parts of the body (Bertrand et al., 2015; Ciais et al., 2013; Smith and Smith, 2007).

1.2 Global Carbon Storage

The dynamics of life depends on the interaction between biogeochemical cycles, particularly the carbon cycle, nutrient cycle, and water cycle. Carbon is normally exchanged in deposits through the transferred reservoir. Deposits can be classified into three main storages: lithosphere, hydrosphere, and atmosphere. Instead, the transfer reservoir is referred to the biosphere. Carbon is transported between these systems naturally through photosynthesis, respiration, decomposition and combustion (Figure 1). CO$_2$ emissions from human activities influence the dynamics of the carbon cycle in the deposits and simultaneously causing the elevation in global temperature; hence, it results in the effect of spontaneous climate change (Arevalo-Madrigal, 2015; Odum and Warrett, 2006).

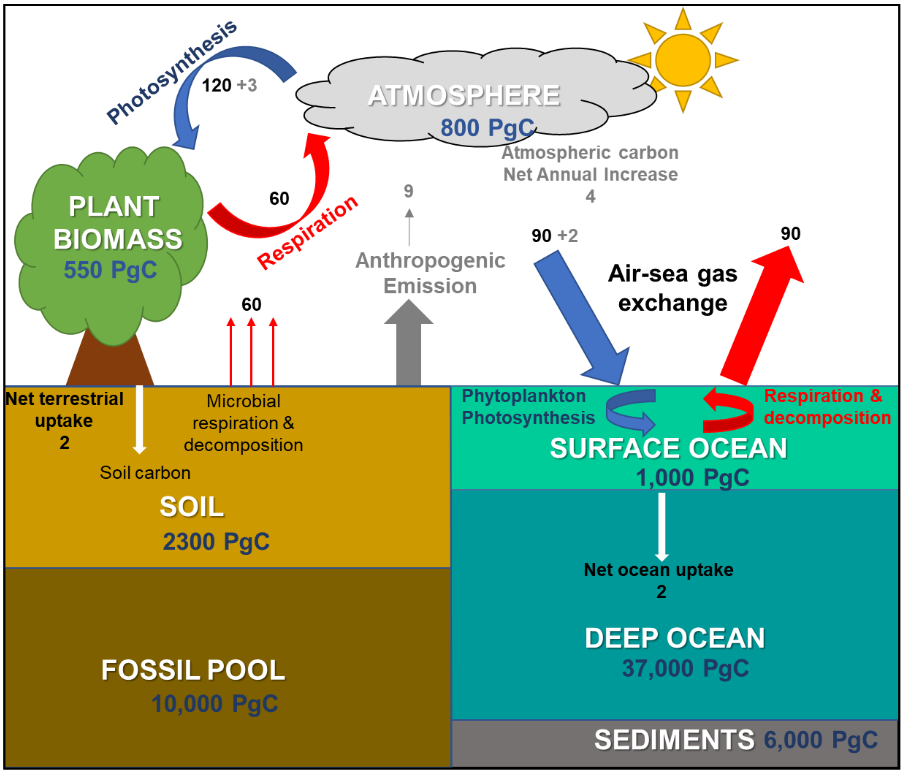

Figure 1. *Global Carbon Cycle Diagram. The amount stored in each deposit, the labels (quantity) in blue symbolize petagram (Pg) of Carbon, while the color-black, and the color-gray refers to Pg/year (Own elaboration, data obtained from U. S. DOE., 2008).*

1.2.1 Lithosphere

The lithosphere is the largest reservoir of carbon, where carbon is stored mainly in sedimentary rocks formed from sedimentation and metamorphic rocks formed from intense temperature and pressure within the Earth crust (University of New Hampshire, 2008). In total, it contains a concentration of 100 million PgC while the hydrocarbons (fossil fuels) occupies a concentration of 4,000 PgC, which are formed by millions of years from the prehistoric living organisms (Smith and Smith, 2007).

1.2.2 Hydrosphere

The hydrosphere forms 71% of the surface of the Earth, containing the vast majority of active carbon stored. Accordingly, 38,000 PgC and more is made of inorganic carbon dissolved as carbonate and bicarbonate ions. Instead, the organic carbon from dead organic matter contains 1,650 PgC while the living organisms occupy 3 PgC. In the ocean surface, the water can absorb CO_2 and most of it forms bicarbonate from the reaction with carbonate ions. However, the water surface is considered the main area of flow between the atmosphere and the hydrosphere due to the rapid exchange of CO_2 through the physical process (dissolution) and biological process (respiration and decomposition) (Smith and Smith, 2007; Turley et al., 2009).

1.2.3 Atmosphere

The atmosphere contains about 750 PgC, which is a small amount compare to other storages. From all the GHGs (Figure 2), CO_2 and CH_4, are the main ones causing global warming, since it accounts to 82% of the total radiative forcing (IPCC, 2015). The concentration of carbon monoxide (CO) is 0.1 ppm, methane (CH_4) 1.6 ppm and most of it is CO_2. Both CO and CH_4 are oxidized to CO_2 by incomplete or anaerobic decomposition of organic matter, and released into the atmosphere. But in the last century, the concentration of CH_4 has doubled by anthropogenic activities, mainly caused by a change in land use and the combustion of fossil fuels. CH_4 is a GHG that absorbs 25 times more heat than CO_2 and also resides longer in the atmosphere; therefore, it has the potential to worsen the issue of global warming (Moriarty and Honnery, 2011; Odum and Warrett, 2006).

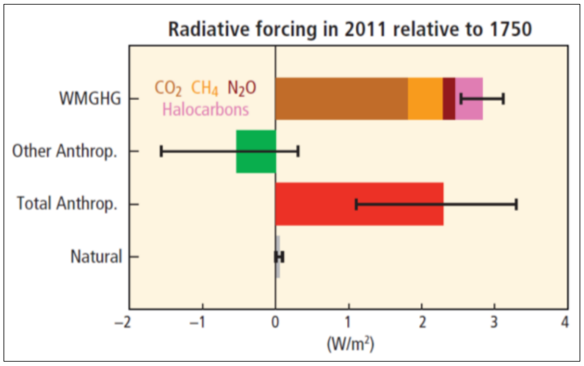

Figure 2. *Radiative forcing of climate change (1750 to 2011). The chart shows the radiative forcing of all GHGs (Adapted from IPCC, 2015).*

1.2.4 Terrestrial Ecosystem

Carbon is stored in plants, animals, soils and microorganisms. The vegetation occupies approximately 4 Gha or 30% of the land area, and stores approximately 560 PgC. In total, forest ecosystems store about 77% of all carbon stored in vegetation, of which approximately 60% of carbon is captured in tropical and subtropical forests, 17 % in temperate forest and the rest in boreal forests. (Nijnik, 2009). The plants absorb CO_2 from the atmosphere and obtain energy from the sunlight during photosynthesis to produce cellulose that allows the growth of stems, branches, roots, leaves, and fruits; but when all components decompose, they contribute to the formation of soil carbon and the remainder is released as gases to the atmosphere (Nijnik, 2009; Odum and Warrett, 2006).

1.2.5 Soil Carbon Pool

The pedological carbon storage (2,500 PgC) is dominated by Total soil carbon (TSC): soil organic carbon (SOC) (1,526 PgC) and soil inorganic carbon (SIC) (945 PgC). The content of SOC varies from low to high, from arid to temperate. Hence, the concentration of SOC is higher in temperate and humid terrains than in hot and dry regions (Lal, 2004). The SOC is normally found in organic waste that is little disrupted from plants, animals, and microorganisms, in the form of humus. This substance is widely distributed in almost all terrestrial and aquatic environments, made from the process of humification. The product tends to chemically interact with complex structures; therefore it has the ability to form soluble and insoluble complexes with metal and hydroxides ions (Martines et al., 2008). The SIC is commonly found in arid and semi-arid climates, in forms of calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$); it is classified as lithogenic inorganic carbon (LIC) and pedological inorganic carbon (PIC). The LIC originates from bedrocks through intemperization to obtain the reaction with calcium and magnesium ions, while PIC is derived from roots and breathing macrobes from the precipitation of carbonate ions. When there is a water deficit, it also limits lixiviation but benefits the accumulation of PIC (Mi et al., 2008).

1.3 Soil Carbon Cycle

As mentioned by various authors (Bertrand et al., 2015; Blume et al., 2016a; Chapman, 2009; IPCC, 2000; Lal, 2008; Monger, 2014; Subke et al., 2010) and shown in Figure 3, carbon changes its state of matter primarily during the process of photosynthesis, assimilation and respiration of autotrophs. Through the same manner, 50% of carbon is fixed in soils predominantly in forms of organic compound (cellulose, hemicellulose, and lignin) and the other 50% released into the atmosphere mainly as CO_2 and CH_4. This phase is known as short-term carbon uptake, in which the Net Primary Productivity (NPP) is estimated after deducting plant respiration from the total organic matter produced. Because of that, the greater the plant productivity the higher is the amount of carbon sequestrated.

The second phase of the cycle refers to heterotrophic respiration or also known as medium-term carbon storage whereby plants are consumed by animals and the Net Ecosystem Production (NEP) is identified from the difference between the NPP and carbon losses (respiration). NEP can be derived in two independent approaches, namely: variation of carbon stocks (vegetation and soils) and CO_2 flux in vegetation.

Lastly, the long-term storage designates the decomposition of organic waste to organic matter. The putrefaction initiates from the feasting of plant debris and animal waste by soil organisms ranging from macro to micro-fauna, breaking it down to smaller fractions. For some plant structures (cellulose and lignin), fungi and bacteria convert it into soluble compounds in the assimilation process through enzymes. This is the process of humification in which humus is the end product. As the cycle continues, mineralization (Jain et al., 2016) occurs as CO_2 dissolved in water forms carbonic acid, reacting with cations to develop secondary carbonate (CO_3) stored as PIC. Contrariwise, weathering of calcium/magnesium silicate minerals (bedrocks) emancipate cations in which it is later precipitated as CO_3 kept as LIC. Since the process of SIC disposition is exceptionally sluggish, it can also be considered as a carbon sink with lower carbon flux.

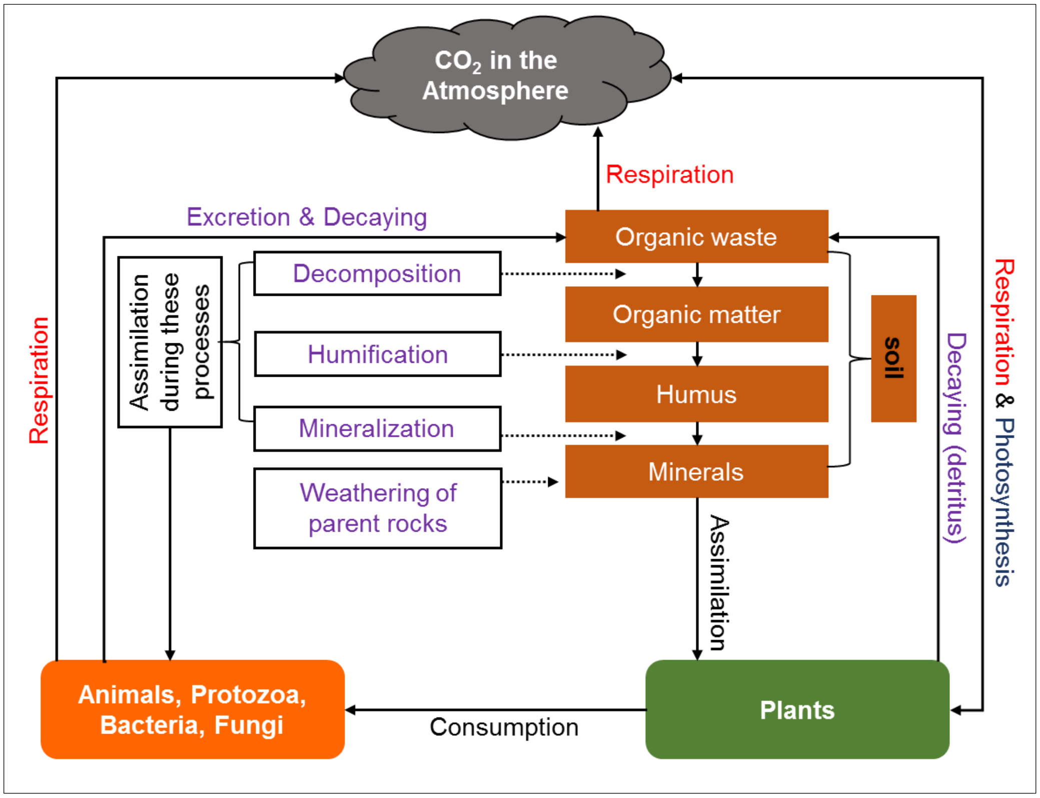

Figure 3. *Soil carbon cycle depicted in three phases contributing to the soil carbon stock. The first phase is the interaction between autotrophs (plants) and atmosphere. The second phase denotes soil carbon after carbon losses in heterotrophic (animals) respiration. The last phase is the accumulation of organic waste from both autotrophs and heterotrophs along with fractions of parent rocks in the soil (Own elaboration, information summarized from Bertrand et al., 2015; Blume et al., 2016; Chapman, 2009; Lal, 2008; Monger, 2014; Rodeghiero et al., 2010).*

1.3.1 Soil organic Matter (SOM)

As mentioned, soil organic matter comprises of residues from different organisms (fungi, bacteria, animals and plants). However, the physiologic cycle of a plant is the most intimate to soil organic carbon (Chapman, 2009). The formation of organic matter primarily derives from leaves, flowers, twigs, bark, fruits, mosses, lichens and fungi, contributing the above-ground litter which gradually becomes part of the soil after decomposition. Moreover, the below-ground materials such as dead roots, mycorrhizal elements and other residues of rhizosphere micro-organisms provide another source for SOM (Subke et al., 2010). Therefore, in summary, SOM is a complex mixture of many different compounds which relies on soil microbial and faunal community (Kutsch et al., 2010; Qiu et al., 2016).

After SOM is fully degraded, it is known as humus, a complex organic compound of brown to dark colored asymmetrical substances whereby further decomposition is very slow. Humic substances consist predominantly of carbon, oxygen, hydrogen, and nitrogen, along with small amounts of sulfur. Humus can be classified in three fractions: humic acids, fulvic acids, and humins (insoluble in acid and alkali solution). Humic acids compose of 51% to 62% of carbon content and are soluble in dilute alkali and insoluble in acids. In contrary, fulvic acids are soluble in acid and alkali solutions but with lower carbon composition (43% to 47%). In general, humic and fulvic acids are similar in structure but differ in molecular weight and functional group contents (Blume et al., 2016b; Guggenberger, 2005; Lutzow et al., 2006; Schnitzer and Khan, 1978).

The quantity of organic matter depends on soil type, soil texture, soil structure, pH, bulk density, the content of stones, water content, biomass, climate, and edaphon. Generally, soil organic content is higher in the topsoil and reduces its concentration with depth, especially in agricultural and grassland soils. Nevertheless, there is an exception in some forest soils. Hence soil horizons are also influenced by the same factors, creating an inter-relationship among edaphons and vegetation types (Bertrand et al., 2015; Martines et al., 2008; Osman, 2013; Qiu et al., 2016; Zech et al., 1997).

1.3.2 Soil minerals in forms of carbonate (CO_3)

Soil inorganic carbon is considered as the second largest carbon sink in the terrestrial reservoir with long-term carbon trapping characteristics. It is found as soil minerals in forms of carbonate. This type of mineral development directly associates with the rock genesis especially in the process of sedimentation. In presence of water, CO_2 dissolution occurs to produce weak carbonic acid and bicarbonate ions, leading to the increase of acidity in the pore solution (Eqs.1a, 1b). These bicarbonate ions intermingle with the cations settling carbonate minerals enhancing the solubility trapping process as the carbonates and bicarbonates rise (Eqs. 2a, 2b, 2c). As the concentration of carbonic acid increases, it undergoes the chemical process of breaking calcium silicate to silicon dioxide when reacting with carbon dioxide and water (Eq. 3) (Shukla Potdar and Vishal, 2016).

Equations:

$$(1a)\ CO_2 + H_2O \rightarrow H_2CO_3$$

$$(1b)\ H_2CO_3 \rightarrow H^+ + HCO_3^-$$

$$(2a)\ Ca^{2+} + HCO_3^- \rightarrow CaHCO_3^+$$

$$(2b)\ HCO_3^- + \text{Metal} \rightarrow \text{Salt} + H^+$$

$$(3)\ 2CO_2 + H_2O + CaSiO_3 \rightarrow Ca^{++} + 2HCO_3 + SiO_2$$

Primarily, SIC is more predominant in forms of calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). As mentioned, the interaction of carbon flux is usually altered in carbonate formation or acidification (CO_2 released) and leaching (Zhao et al., 2016). Therefore, Liu (2011) stated that additional CO_2 may not be captured during pedogenic process of carbonate construction, since dissolution and precipitation of carbonate parent material receive and liberate an equal amount of carbon (Eq 4). However, PIC derived from root dissolution and microbial CO_2 into soil water and carbonate is of great potential when carried by surface runoff, since it consumes two moles of atmospheric CO_2 for every mole liberated (Eqs 5 and 6) (Jin et al., 2014).

$$(4)\ CaCO_3 + H_2O + CO_2 \leftrightharpoons 2HCO_3^- + Ca^{2+}$$

$$(5)\ 2CO_2 + 3H_2O + CaSiO_3 \rightarrow H_4SiO_4 + 2HCO_3^- + Ca^{2+}$$

$$(6)\ 2HCO_3^- + Ca^{2+} \rightarrow CaCO_3 + H_2O + CO_2$$

CHAPTER 2 LITERATURE REVIEW

2.1 Soil Carbon Stocks

2.1.1 Global SOC

Since there are few information on spatial distribution of soil carbon stock, the Harmonized World Soil Database (HWSD) estimates the carbon stock in Figure 4 using spatial data by multiplying soil carbon content with soil thickness, dry bulk density, and volume of stones. During soil carbon estimation, topsoil (0-10 or 0-30 cm) and subsoil (1.5 times the amount of Organic Carbon of the topsoil) are considered in the SOC stock calculation. From the result assumed, there is a higher SOC content in the Northern Hemisphere of the globe. With the relation to the study area, the Peninsula of Yucatan is considered a region of high SOC stock. Therefore, the relation of factors contributing to the SOC sequestration is important to comprehend the dynamics of carbon flux in the region (Hiederer and Köchy, 2011).

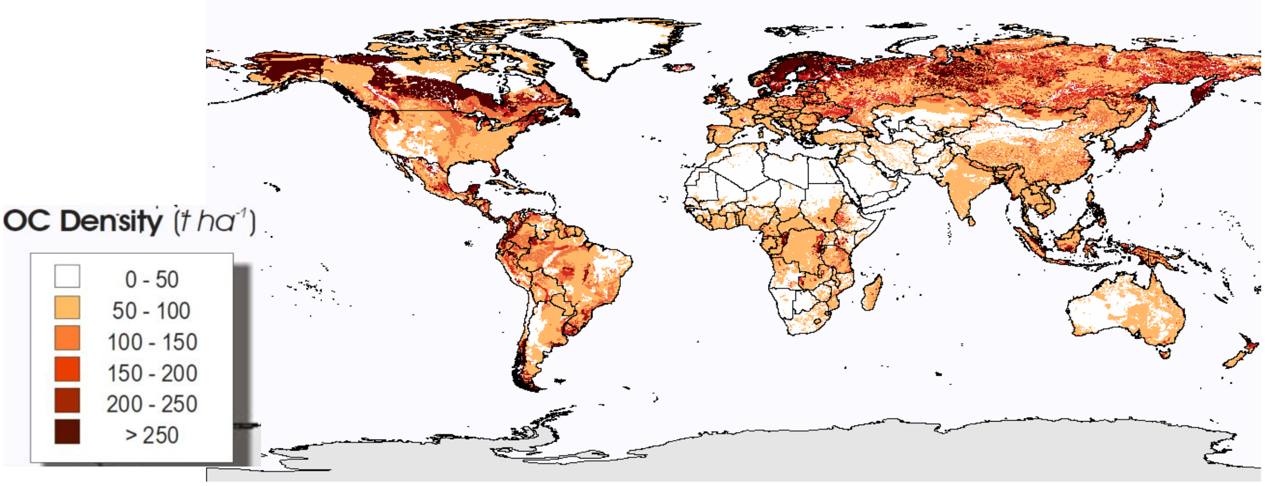

Figure 4. *Global Soil Organic Carbon Density (t ha^{-1}) for Combined Topsoil and Subsoil Layer from Amended HWSD (Hiederer and Köchy, 2011).*

2.1.2 Distribution of Carbon in different Soil Types

The global soil carbon stock estimated by Eswaran et al., (2000) adjusted in Table 1 (Lal, 2004), shows the soil carbon density per soil type. The soil classification from the Twelve Orders of Soil Taxonomy (USDA, 2014) was used to estimate global SOC and SIC. In Mexico, World Reference Base (FAO, 2014) is used to classify national soil types; thus, a column (WRB) is added to better understand the reported carbon content (Table 1) estimated using Soil taxonomy. In Table 1, the organic carbon density is greater than the inorganic carbon density. In addition, for SOC, Gelisol is the most abundant in the carbon sink while the least is dominated by shifting sand. In the case of SIC, Aridisols is the largest carbon pool while there was no carbon estimated in Andisols, Histosols, Oxisols, Spodosols, Ultisols and rocky land. Considering one of the most abundant soils in the study area, Leptosol has a large surface area but with low SOC retention but in contrary the SIC density is significant.

Table 1: Estimates of Soil Carbon Stocks to 1 m depth

			SOC		SIC	
Soil Taxonomy	**World Reference Base (WRB)**	**Area (Mha)**	**Density (tons/ha)**	**Pool (PgC)**	**Density (tons/ha)**	**Pool (PgC)**
Alfisols	Luvisols, Lixisols	1262	125	158	34	43
Andisols	Andosols	91	220	20	0	0
Aridisols	Calcisols, Gypsisols, Solonchaks, Solonetz	1570	38	59	290	456
Entisols	Arenosols, Fluvisols, Leptosols, Regosols, Umbrisols	2114	42	90	124	263
Gelisols	Cryosols	1126	281	316	6	7
Histosols	Histosols	153	1170	179	0	0
Inceptisols	Cambisols	1286	148	190	26	34
Mollisols	Chernozems, Gleysols, Kastanozems, Phaeozems	901	134	121	96	116
Oxisols	Alisols, Ferrasols, Nitisols, Plinthosols	981	128	126	0	0
Rocky land		1308	17	22	0	0
Shifting sand		532	4	2	9	5
Spodosols	Podzols	335	191	64	0	0
Ultisols	Acrisols, Alisols	1105	124	137	0	0
Vertisols	Vertisols	316	133	42	50	21
	Total	**13083**		**1526**		**945**

Source: Own elaboration, data obtained from Lal (2004). The association between different soils classification (Soil Taxonomy and WRB) is derived from different sources (De Jong et al., 2002; FAO, 2014; Morand, 2010; Tripathl and Psychas, 1992).

2.1.3 Distribution of Soil Carbon in Vegetation Types

Due to different climatic regions and vegetation type, Table 2 and 3 are demonstrated to compare the estimated soil carbon stock reported by different authors. The Table 2 shows the soil carbon stored within each climatic region according to the IPCC. By summing the total storage of tropical region, the estimated value is roughly 471.3 PgC (Scharlemann et al., 2014). In comparison with the distribution to the ecosystem, the tropical region (Table 3) has a total ranging from 460 to 480 PgC (Lal, 2004). The results in Table 2 and 3 are similar, but are not precise; since cropland and wetland of the tropical region were not estimated. By looking at the total soil carbon estimated by different authors (Eswaran et al., 2000; Hiederer and Köchy, 2011; Lal, 2004; Scharlemann et al., 2014), the total value of SOC from Table 1 and 2 are the closest to the value 1,500 PgC mentioned by Odum and Warrett (2006). On the other hand, Table 3 has values similar to the estimation done by U. S. DOE (2008). Therefore, the assumed soil carbon has a value between 1,500 and 2,500 PgC, which portrays a large interval of standard errors. In addition, from the carbon density presented in Table 3, probably SIC was also estimated in the calculation; hence, the value projected might contain great sources of error.

Table 2: Estimates of Soil Carbon Contents in relation to Climatic Region

	SOC (PgC)			Phytomass (PgC)	Terrestrial carbon pool (PgC)
IPCC Climate Region	**Topsoil**	**Subsoil**	**Total**		
Tropical wet	62.60	65.40	128.00	140.20	268.20
Tropical moist	78.60	72.30	150.90	151.70	302.60
Tropical dry	67.30	69.00	136.30	42.50	178.80
Tropical montane	29.60	26.50	56.10	40.50	96.60
Warm temperate moist	33.30	29.70	63.00	28.70	91.70
Warm temperate dry	38.90	39.60	78.50	24.20	102.70
Cool temperate moist	104.10	106.20	210.30	28.50	238.80
Cool temperate dry	52.20	50.00	102.20	9.10	111.30
Boreal moist	162.00	194.70	356.70	23.50	380.20
Boreal dry	32.00	37.00	69.00	5.10	74.10
Polar moist	30.60	21.70	52.30	2.20	54.50
Polar dry	8.00	4.30	12.30	0.50	12.80
Total	**699.00**	**716.00**	**1416.00**	**497.00**	**1912.00**

Source: Own elaboration, data obtained from Scharlemann et al. (2014).

Table 3: Estimates of Soil Carbon Contents in relation to Ecosystem

Ecosystem	**Area (10^9 ha)**	**SOC (PgC)**	**SOC density (tons C/ha)**
Tropical Forest	1.76	213-216	121-123
Temperate Forest	1.04	100-153	96-147
Boreal Forest	1.37	338-471	247-344
Tropical savannas and grasslands	2.25	247-264	110-117
Temperate grassland and scrub	1.25	176-295	141-236
Tundra	0.95	115-121	121-127
Desert and semi-desert	4.55	159-191	35-42
Cropland	1.6	128-165	80-103
Wetlands	0.35	225	643
Total	**15.00**	**1701-2101**	**1594-1882**

Source: Own elaboration, data obtained from Lal, (2004).

2.2 Methods to enhance carbon sequestration

Cropland management has been one of the major factors affecting the carbon flux. Cropland management can be classified into the restoration of degraded lands, crops rotation, tillage, Land-use change, and agroforestry (Reddy, 2015).

2.2.1 Restoration of degraded lands

According to Prayogo (2013), the use of short rotation coppice (SRC) is a method to restore degraded land since it can improve soil quality. Besides the contribution to the soil, it is also a mitigation method to climate change since it grows rapidly (absorbs large amount of carbon from the atmosphere), can be harvested over long periods of time (15-30 years), can adapt to poor soil and low water availability, purifies wastewater and can be used as biofuel which serves as an additional income for farmers. Similarly, Zimmermann (2013) explained in his thesis that *Miscanthus*, an SRC has a high carbon sequestration potential due to its physiological properties. It translocates aboveground carbon into below ground during the winter to enhance the harvest in spring. In addition, it reduces aeration in the soil which promotes the increase in SOC stability and reduces the mineralization rate, hence it fosters the SOC sequestration rate.

2.2.2 Crop Rotation

Rotation of crops is one of the methods that can enhance the soil carbon stock by determine at what season of the year and which type of crop to cultivate. On the experiment done by Zierfuss (2013), pasture contributes to a greater amount of SOC than crops. Moreover, the treatment to compare the rotation of crops, soybeans use as a second crop after wheat cultivation had a higher concentration in SOC sequestration. Thus, adequate land use management for crop cultivation is very important to obtain the highest productivity.

2.2.3 Tillage and No-tillage

Another method to increase SOC is practicing a reduced tillage. No-tillage management is the most efficient approach to SOC capture in cropland. It minimizes the rate of carbon loss associated with soil erosion, decreases fossil fuel emissions because of little or no tractor use and reduces the rate of SOC decomposition (Desjardins et al., 2005). From many studies, conventional tillage may result in SOC losses since it accelerates the microbial oxidation of SOC, thereby increases soil temperature and aeration; hence, it results in a change of carbon storage from soil to the atmosphere. However, no-tillage practices have a positive impact of SOC sequestration (Prayogo, 2013).

2.2.4 Land-use change

Globally, land-use is classified into five main categories: Forest Land, Cropland, Grassland, Wetland, Settlement and Other land (IPCC, 2006). In Mexico, vegetation type of each category mentioned (Forest Land, Cropland, Grassland and Wetland) is sub-classified according to vegetation characteristics and composition (INEGI, 2015a). Due to diverse conditions and environmental factors of the region, the classification of INEGI is more suitable for soil carbon stock estimation in the study area since IPCC classifies the sub-division of Forest Land for the entire Peninsula of Yucatan using only one classification, Tropical moist deciduous forest.

According to the Report of National Inventory of GHGs Emission for the year 1990 to 2006 (De Jong et al., 2006), grassland emits the highest amount of CO_2, followed by cropland while forestland contributed the least. In the research of land-use and cropping effect on soil carbon, Chaudhury et al. (2016), explains the same phenomenon.

For soil carbon sequestration, the comparison of land-use among agriculture (maize-wheat), forest, horticulture (citrus and mango) and degraded land shows that the SOC content decreases as the depth increases. The SOC concentration is considered to be the highest in forestry, followed by horticulture; while the least efficient is agriculture (Sharma et al., 2014). When comparing cropland with middle-aged forestland, the SOC concentration of middle-aged forest is 33% higher than croplands (Wang et al., 2016). Accoring to the experiment done by Deng et al. (2016), the age of cropland abandoment and the land-use change types showed significant effect on soil carbon sequestration. In addition, he mentioned that shrubland is a better restoration in getting long-term soil carbon than grassland and forestland. In Mongolia, the research conducted portrays that the conversion of grassland to cropland is less effective in carbon sequestration than improving grassland management (He et al., 2012). Similarly, Post and Kwon (2000) states that the conversion from cropland to grassland may lead to an increase in SOC. In short, SOC content in soil is highly correlated with the decomposition of litter from the different land-uses. Although grassland shows significant effect on soil carbon sequestration, it also emits high amount of CO_2. Therefore, forestland is considered the best land-use for soil carbon sequestration.

2.3 Challenges of soil carbon estimation

2.3.1 Carbon Flux

Although soil carbon is considered as one of the largest carbon pools, the flux estimation continues to bear a high range of standard errors (Kutsch et al., 2010). There are varieties of carbon inputs but generally, it is referred to as litter from different organisms. During the litter decomposition, the dead organic material is broken down into smaller organic molecules primarily in forms of H_2O, CO_2 and mineral components. The decomposition rate ranges from days to thousands of years. The amount stored in soils is controlled by the photosynthesis rate of the vegetation type, quantity of faunas, litter quality, climatic and soil conditions, soil disturbances, limited oxygen availability, and soil microbial activities. Moreover, the result of soil carbon loss is the effect of erosion processes, changes in the chemical composition of SOM and organism's respiration (Cotrufo et al., 2010; McBratney et al., 2014; Prayogo, 2013).

According to Kuzyakov (2006), a complete understanding of the CO_2 flux in soils is still insufficient; hence, the author breaks down the major contributor pools into five groups: root respiration, microbial decomposition, microbial respiration, organic matter decomposition and basal respiration derived from SOM. On the other hand, Cheng and Gershenson (2007), explain the principle of belowground carbon cycling by summarizing it into respiration and decomposition of organic matter. Respiration can be subdivided into rhizosphere and microbial respiration. Contrary, decomposition relates itself with the microbial and chemical decomposition of SOM. Despite the unlikelihood of the two processes, they both are associated with rhizosphere interactions, and the rate of carbon flux may be affected by a number of nutrients and water availability at 30 to 80 percent. The rate of CO_2 released from the soil is altered principally by microorganisms as the temperature rises, demonstrating a high positive correlation. Consequently, there is still a lack of accuracy in the carbon stock estimation in relation to the respective geographic and environmental conditions (Epron, 2010; Moyano et al., 2010).

2.3.2 Methods of Soil Carbon Estimation

There are several procedures to identify the SOC stock changes such as flux approach, repeated inventory approach and changes in specific fractions approach (De Jong et al., 2006, 2002; IPCC, 2006; Rodeghiero et al., 2010; Soto-Pinto et al., 2005). However, the detection of small changes in the net SOC change over time is still a problem when examining a large volume of soil carbon stock (Rodeghiero et al., 2010). In addition to that, the methodology to estimate the actual carbon content in soils can be scrutinized using different approaches; thus, each of the methods has advantages and disadvantages. The most common methods used are geospatial strategy (Kumar et al., 2016), geostatistical method (Baggaley et al., 2016), visible-near infrared (Vis-NIR) (Peng et al., 2014), isotopic analysis (Nordt et al., 1998), Walkley-Black Method (WB), pressure calcimeter method, dry combustion, loss-on-ignition (LOI), and elemental analyzer (CNHS-O) (Kusumo, 2009; Rodeghiero et al., 2010; Wang et al., 2012; Xuan, 2015).

The geospatial method estimates carbon content using bare soil index (BSI) and normalized difference vegetation index (NDVI) (Kumar et al., 2016). The use of spectral indices derived from remote-sensing imagery for SOC stock came about from Vis-NIR spectroscopy using the wavelength to analyze the carbon content. Satellite imagery is a less costly approach but requires previous studies on soil properties (Peng et al., 2014, 2015). Though geospatial and geostatistical approaches are used to map large surface areas, the analysis in the laboratory continues to serve as the source of reference, therefore; comparisons between the basic methods are important. According to Kusumo (2009), Rodeghiero et al. (2010), Wang et al. (2012), and Xuan (2015), measuring SOC using traditional methods (Walkley-Black, dry combustion, and loss-on-ignition) are quite time-consuming and effortful. For instance, the Walkley-black procedure provides an incomplete measure of SOC and reports high standard errors with extreme low SOM. In the case of dry combustion, the quantification of SOC is less preferred in the presence of SIC since the measurement of SOC is not straightforward. On the other hand, the loss-on-ignition method overestimates SOM due to the high temperature which degrades inorganic components while heating the soil sample. In general, all these methods require a correction factor. The challenge behind this is the selection of a method for a specific climatic and geomorphologic region.

CHAPTER 3 STUDY AREA

3.1 Location (topography)

The state of Quintana Roo is a territory in the XI physiographic province of Mexico called Peninsula of Yucatan. The territory represents 2.5% of the entire country with an area of 5,084,300 ha. It is located in southeastern Mexico between the latitude 17°49' N and 21°36' N, and Longitude 86°44' W and 89°24'52" W. In the north Qunitana Roo borders on with the state of Yucatan, in the south with Belize and Guatemala, in the east with the Caribbean Sea, and in the west with the state of Campeche. The state of Quintana Roo is considered a region of low flat topography with surface and littoral erosion easing the process of karstification. In addition, the topography is established by tectonic fractures that cause the alignment of hills and dolines (Fragoso-Servón, 2015; Krasilnikov et al., 2013).

3.2 Climate

Quintana Roo is considered a region with equatorial savannah climate characterized by dry winters (Aw according to the Köppen classification) (Figure 5) (Kottek et al., 2006). It presents warm subhumid characteristics due to the local factors such as marine influences, the absence of orographic prominences and tropical depressions (INEGI, 2002). The mean annual temperature is higher or equals to 26°C and the mean annual precipitation is approximately 1,200 mm with a relatively standardized distribution across the entire state. January is the coldest month, while the warmest can fall before or after the summer solstice i.e. May, June, July or even August; but in each season the temperature is uniform. The hottest months are from May to September with temperatures ranging from 25°C to 29°C; the colder ones go from December to February, fluctuating between 21°C and 24°C. The rainy season comprises the months of May to October, although sometimes it lasts until November. The dry season covers the months of November to April, and this period can be divided into two subperiods. The north period is from November to February, caused by air masses and clouds with polar winds accompanied by violent gusts and low temperatures. The natural drought period starts from February and ends in April. In the case of precipitation, the month of September contributes the highest amount of rainfall with an estimation of 207.5 mm while March is the least with 32.2 mm (Fragoso-Servón, 2015; INEGI, 2002; Pereira-Corona et al., 2013). The trade winds dominate absolutely over summer and early autumn reducing their intensity in winter and the direction of the wind flows from east to southeast. Tropical depressions and cyclones usually occur during the months of May to June (Fragoso-Servón, 2015; Herrera-Sansores, 2011).

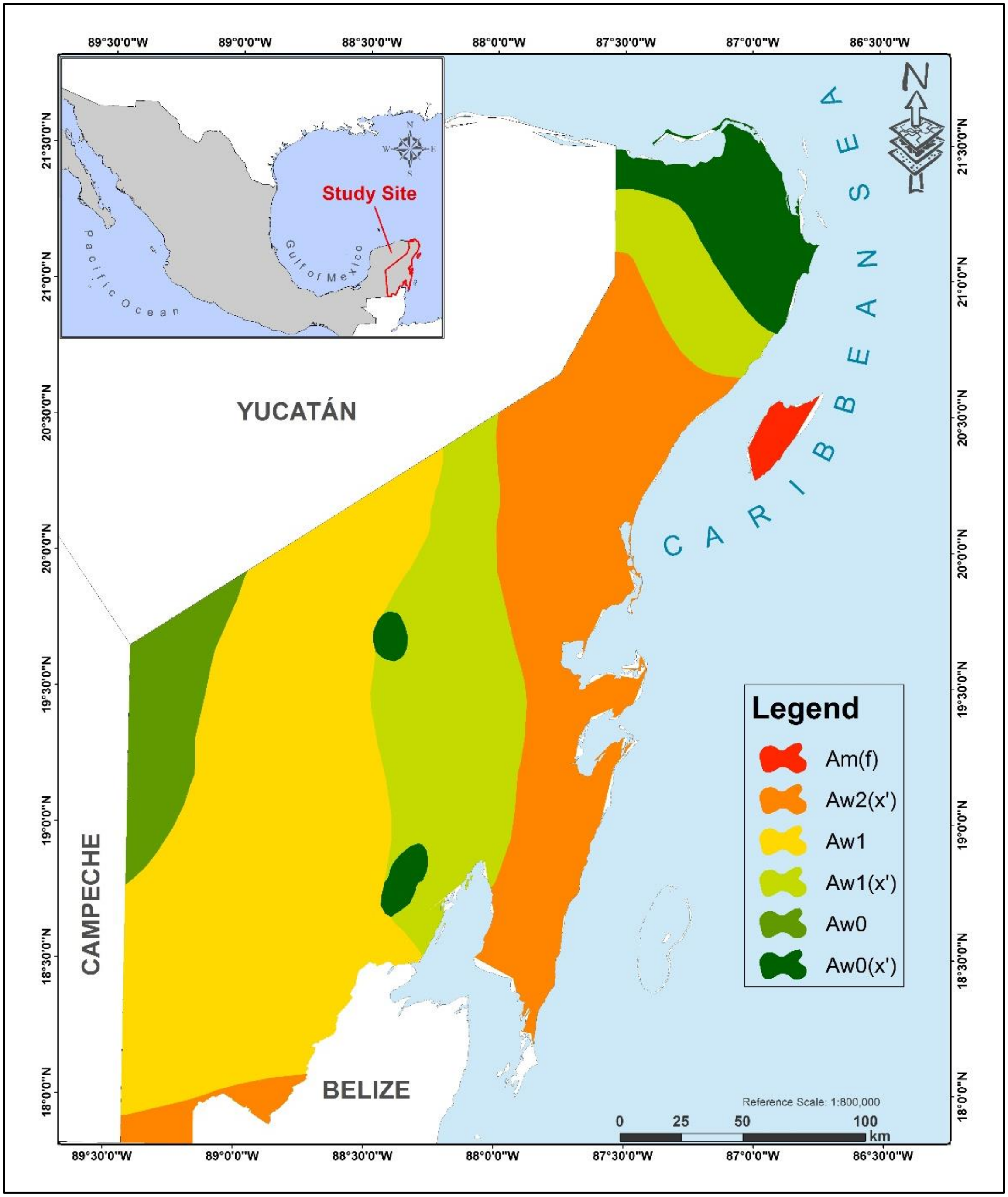

Figure 5. *Climate sub-classification in the State of Quintana Roo.* ***Am(f)****: warm subhumid, high humidity, rain in summer;* ***Aw$_2$(X’)****: warm subhumid, high humidity, winter rain between 5 to 10.2 mm;* ***Aw$_1$****: warm subhumid, medium humidity, winter rain between 5 t0 10.2 mm; ;* ***Aw$_1$(X’)****: warm subhumid, medium humidity, winter rain > 10.2 mm;* ***Aw$_0$****: warm subhumid, low humidity, winter rain between 5 to 10.2 mm;* ***Aw$_0$(X’)****: warm subhumid, low humidity, winter rain > 10.2 mm (Own elaboration, data obtained from INEGI, 2008).*

3.3 Geology and Geomorphology

The geologic composition of the territory is made up of sedimentary rocks which comprise of limestones, dolomites, and evaporites that overlie igneous and metamorphic basement rocks. The interior part of the province is composed of carbonate rocks from Eocene-Paleocene periods. The coastal region is mainly formed from Miocene-Pliocene deposits that settle on the Quaternary-age strata. During the Cenozoic Era, the continuous process of emersion and submersion allowed the erosion of sediments of the Paleocene that gives rise to the basic platform of the Peninsula; hence the orography of the territory is a flatland with little elevation (INEGI, 2002; Kambesis and Coke IV, 2013; Krasilnikov et al., 2013).

According to Fragoso-Servón (2015), the Peninsula of Yucatan has continued emerging. This neo-tectonic activity has caused the southern province to rise with a shift in the clockwise direction. This phenomenon has led a fractured oriented system to the north and northeast. Thus, the crack, fracture, and geologic failure are the factors that manipulate the position of the karst formation. These geologic failures are elongated with a depth of 10 to 20 m and several hundreds of meters wide. When these fractures are filled with water, the subterranean runoff forms lagoons and in other special cases, it develops natural sinkholes. Therefore, karstification, cracks, and fractures of rocks are prominent to these lithologic effects.

According to Tello-Taracena and Castellanos-Martínez (2011), the relief of the State of Quintana Roo is a flatland with slopes that consist of a slight inclination that declines from west to east towards the Caribbean Sea. The average height of the territory is approximately 10 masl. According to the description by INEGI (2002), the Peninsula of Yucatan can be subdivided into three physiographic provinces namely (Figure 6): Karst and Ridge of Campeche, Karst of Yucatan and Lower Coast of Quintana Roo. The Karst and Ridge of Campeche is the province with the highest altitude that lies to the south of the territory. This physiographic sub-province established low ridges and small plains that descend from west to east in a stepped-wise manner ranging from 300 masl to 10 masl or less. The Karst of Yucatan is a sub-province with plainland consisting of slight slopes made of limestones. The karstic topography led to the formation of sinkholes or dolines; thus, it establishes a natural superficial drainage system. In contrary, the Lower Coast of Quintana Roo extends along the eastern edge of the State and is characterized by its stepped relief with a reduced elevation from west to east. Along the southern and southeastern of the territory circulates the Río Hondo. In the same sub-province, many natural sinkholes such as Cenote Azul; several lagoons such as Bacalar, San Felipe, La Virtud, Chile Verde and Laguna Guerrero can be found.

3.4 Hydrology

The State is in the tropical zone of the southeast of the country where precipitations are abundant with estimation greater than 1,000 mm. The infiltration capacity of the land provokes the majority of water penetration (80%) into the aquifer; the remainder (20%) is distributed to vegetation, superficial runoffs and other water bodies (lagoons, dolines, lakes, and ponds) (Fragoso-Servón, 2015).

Surface currents usually form dendritic networks, continuous runoffs, and losses through evaporation and, infiltration. The regime of most streams with some exceptions is intermittent since many of them only circulate in the presence of slope and penetrate into the soil. Due to the nature of the geological substrate that contains highly soluble limestone, karstic characteristics and poor relief, there are no surface water currents in exception of Río Hondo. Other surface water bodies are mainly coastal and the interior water bodies are mostly located in the southern part of the state, primarily intended for recreational and domestic uses (Herrera-Sansores and Heredia-Escobedo, 2011).

According to INEGI (2002), the state of Quintana Roo belongs to two hydrological regions (HR): HR 32 Northern Yucatan (Yucatan) and HR 33 Eastern Yucatan (Quintana Roo). The HR 32 not only includes the state of Quintana Roo but also Yucatan and Campeche with a total surface area of 56,443 km^2; the area of study covers approximately 32% of the hydrologic region, which includes the islands (Cozumel, Isla Mujeres and Isla Contoy). Due to high infiltration and scarce relief, there are no water bodies of great importance; however, there are small lagoons such as Cobá, Punta Laguna, and La Unión. Conversely, the HR is characterized as the international border that extends to the Central American Countries (Belize and Guatemala) constituted by the Río Hondo.

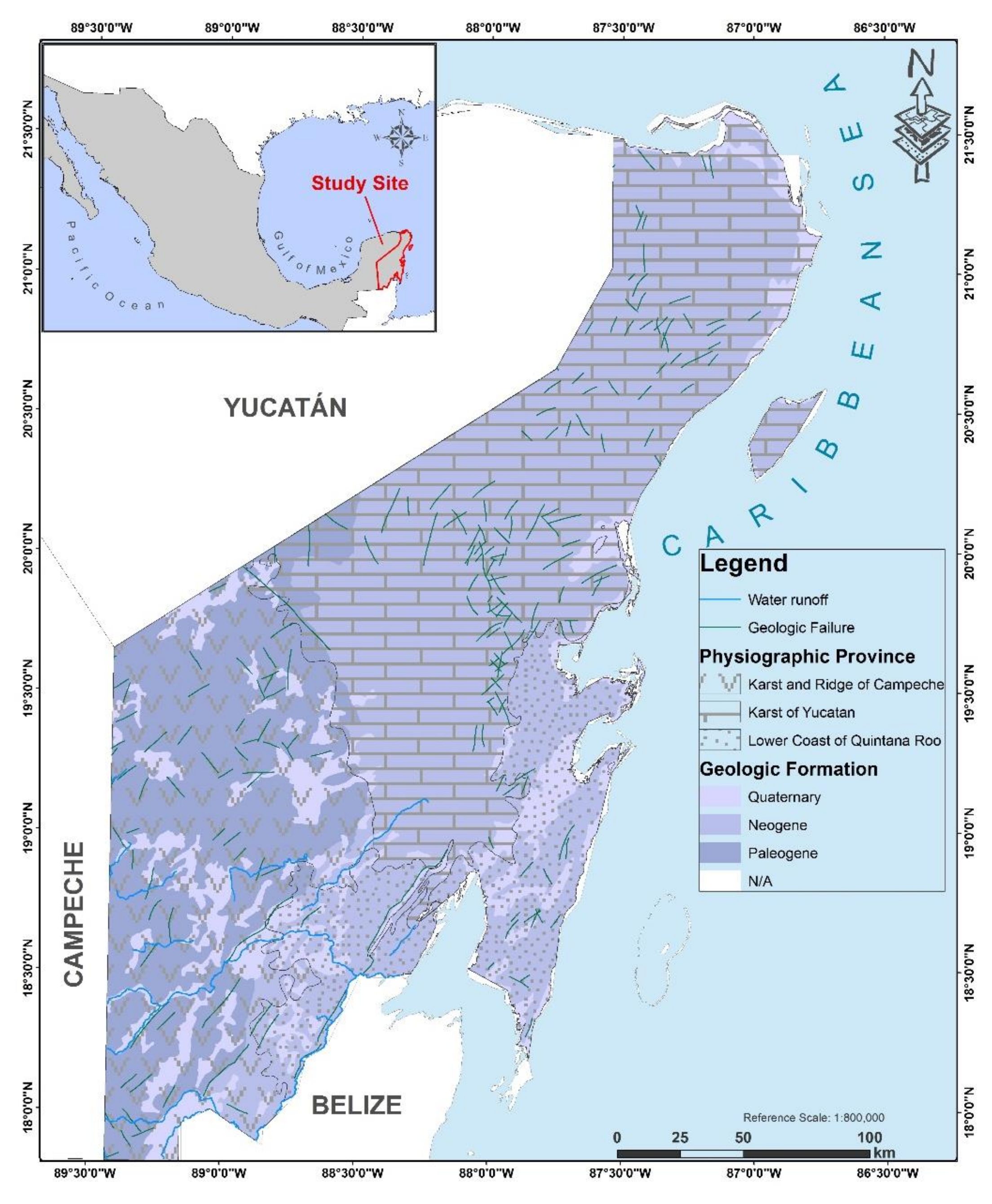

Figure 6. *Geomorphologic formation in the State of Quintana Roo. This territory can be subdivided into three physiographic provinces namely: Kart and Ridge of Campeche, Karst of Yucatan and Lower coast of Quintana Roo (Own elaboration, data obtained from INEGI, 2008b, 2001).*

3.5 Soil types, distribution, and characteristics

In general, soils in the state are newly formed and have not yet reached their edaphic maturity; hence soil depth is rather shallow. In the south and west region (Figure 7), there are more evolved soils (Vertisols, Luvisols, Cambisols, and Nitisols), lying on the ancient geological plates, while to the north and east, it is less aged (Pereira-Corona et al., 2013). According to INEGI (2013a), the main soils include those mentioned along with Arenosols, Calcisols, Fluvisols, Gleysols, Histosols, Leptosols, Lixisols, Phaeozems, Regosols and Solonchaks. The predominant soil type in the state is Leptosol, which is developed mainly from consolidated sedimentary rocks and metamorphic rocks.

According to the world reference base for soil resources (FAO, 2014), soils can be classified in eight great categories: thick organic layers, strong human influence, limitations to root growth, soils distinguished by iron (Fe) or aluminum (Al), dark topsoil, salts or non-saline substances, clay-enriched subsoil, and little or no profile. In the study area, there are six of them. From the 13 sampled soils, Histosols are considered as soils with thick organic layers. Leptosols, Vertisols, and Solonchaks belong to the soil group that limits root growth. Gleysols and Nitisols are distinguished by Fe/Al while Kastanozems and Phaeozems contain a pronounced accumulation of organic matter in the topsoil. On the other hand, Luvisol has a high content of clay stored in the subsoil. Lastly, Cambisols, Arenosols, Fluvisols, and Regosols are characterized as soils with moderate or no profile development.

As mentioned by Fragoso-Servón (2015) (Table 4), Leptosol is the most predominant soil in the State of Quintana Roo occupying 77.10% of the area. This type of soil is very shallow (less than 25 cm deep) and stony (80% covered by rocks). The second dominant soil is Phaeozem (7.30%). It is rich in organic matter and is normally associated with Leptosols and Vertisols. The third largest is Vertisol (6.70%), which is brown in color and contains high clay content. During the dry season, the soil dries out and form deep wide cracks. In the south and southeast of the territory, this soil is used mainly in agriculture.

Table 4: The surface area occupied by each Soil Type

Soil Type	Area (ha)	%
Leptosol	31954230.60	77.10
Phaeozem	3030809.81	7.30
Vertisol	2795894.90	6.70
Gleysol	1876004.36	4.50
Luvisol	595922.54	1.40
Solonchak	508112.70	1.20
Arenosol	256796.22	0.60
Regosol	244010.94	0.60
Histosol	81233.67	0.20
Nitisol	68554.56	0.20
Cambisol	46423.56	0.10
Fluvisol	984.90	0.002

Source: Own elaboration, data summarized by Fragoso-Servón (2015) from INEGI (2013a).

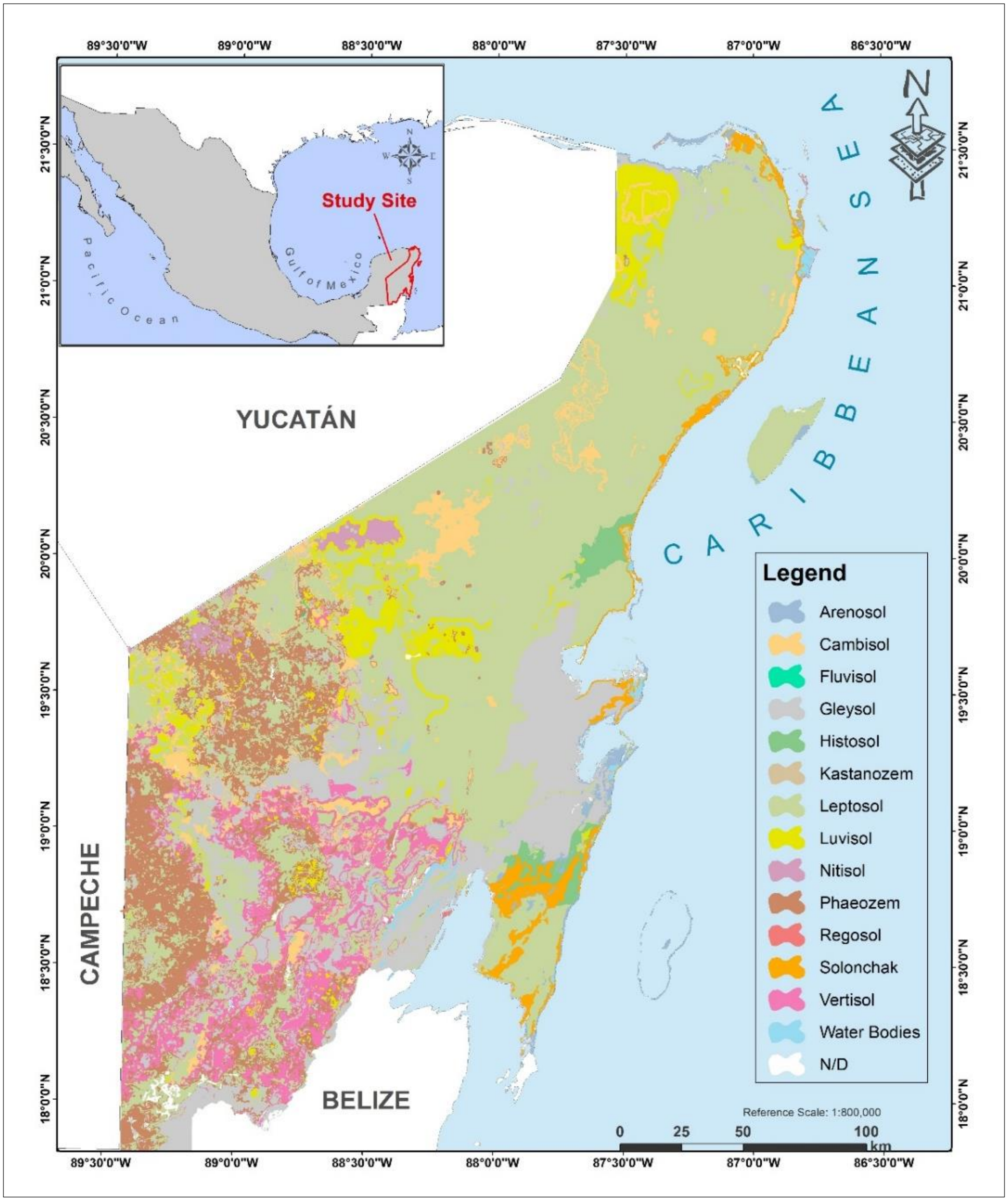

Figure 7. *Distribution of soils in the State of Quintana Roo. (Own elaboration, data obtained from Fragoso-Servón, 2015; INEGI, 2013a)*

3.6 Actual land cover

The State of Quintana Roo allows the development of a lush vegetation of the neotropical region. In the state, there are different types of vegetation (Figure 8), due to the geological characteristics, soil types, topography and the presence of the Caribbean Sea (Ek-Díaz, 2011). According to INEGI (2015a), forests are classified as high (over 30 meters), medium (between 15 and 30 m), or low (less than 15 m). Secondly, they are characterized by foliage lost. They are considered evergreen (less than 25% of species lose their leaves), semi-evergreen (25 to 50% of the species lose the leaves), semi-deciduous (50 to 75% of the species lose the leaves) or deciduous (more than 75% of the species lose their leaves).

The dominating vegetation units found in the state are semi-evergreen high rainforests (SeHF), semi-deciduous medium rainforests (SdMF), semi-evergreen medium rainforests (SeMF), thorny low rainforests (TLF), semi-deciduous low rainforests (SdLF), semi-evergreen low rainforests (SeLF), flooded low rainforests (FLF), natural palms (NP), induced palms (IP), mangroves, coastal dune vegetation (CDV), coastal shrublands (CSl), and wetlands (savannas, thule swamps, and marshland vegetation) (Miranda and Hernández, 1963; Rzedowski, 2006). In the state of Quintana Roo semi-evergreen medium rainforests predominate. This vegetation contains many epiphytes, bromeliads, ferns, mosses, orchids, and lianas. Among the most abundant species are *Lysiloma latisiliquum, Brosimum alicastrum, Bursera simaruba, Manilkara zapota,* and *Lysiloma spp*. The semi-deciduous medium rainforest is a very dense vegetation community that usually forms a uniform canopy. It is normally found in between the state of Yucatan and the state of Quintana Roo. The most frequent and abundant species are *Lysiloma latisiliquum, Piscidia piscipula, Byrsonima crassifolia,* and *Chrysophyllum mexicanum*. The thorny low rainforest is a vegetation type with a height less than 8 m and can normally be found in regions where soil is flooded during the wet season. The most common species are *Haematoxylum campechianum, Bucida buceras, Cordia dodecandra,* and *Leucaena spp*. The semi-evergreen low rainforest is a vegetation type that usually suffers from flood during rainy season. The average height of this community is less than 5 m and the dominant species are *Byrsonima crassifolia, Byrsonima bucidaefolia, Crescentia alata, Coccoloba spp.,* and *Metopium brownei*. For the semi-deciduous low rainforest, *Lysiloma latisiliquum, Pseudophoenix sargentii,* and *Bursera simaruba* are the most abundant. For mangrove communities, the tree height ranges from around three to five meters, and the mangrove stands are commonly dominated by *Rhizophora mangle, Laguncularia racemosa, Avicennia geminans,* and *Conocarpus erectus*. Lastly, other vegetation communities such as palms (*Scheelea liebmannii, Orbignya guacoyule, Paurotis wrightii,* and *Sabal pumos*), thule swamps (*Typha spp., Scirpus spp.* and *Cladium jamaicense*), marshland vegetation (*Thalia geniculata, Calathea spp.,* and *Heliconia spp*.), and savannah vegetation occupy a smaller proportion (Fragoso-Servón, 2015; INEGI, 2013b, 2015a; Krasilnikov et al., 2013).

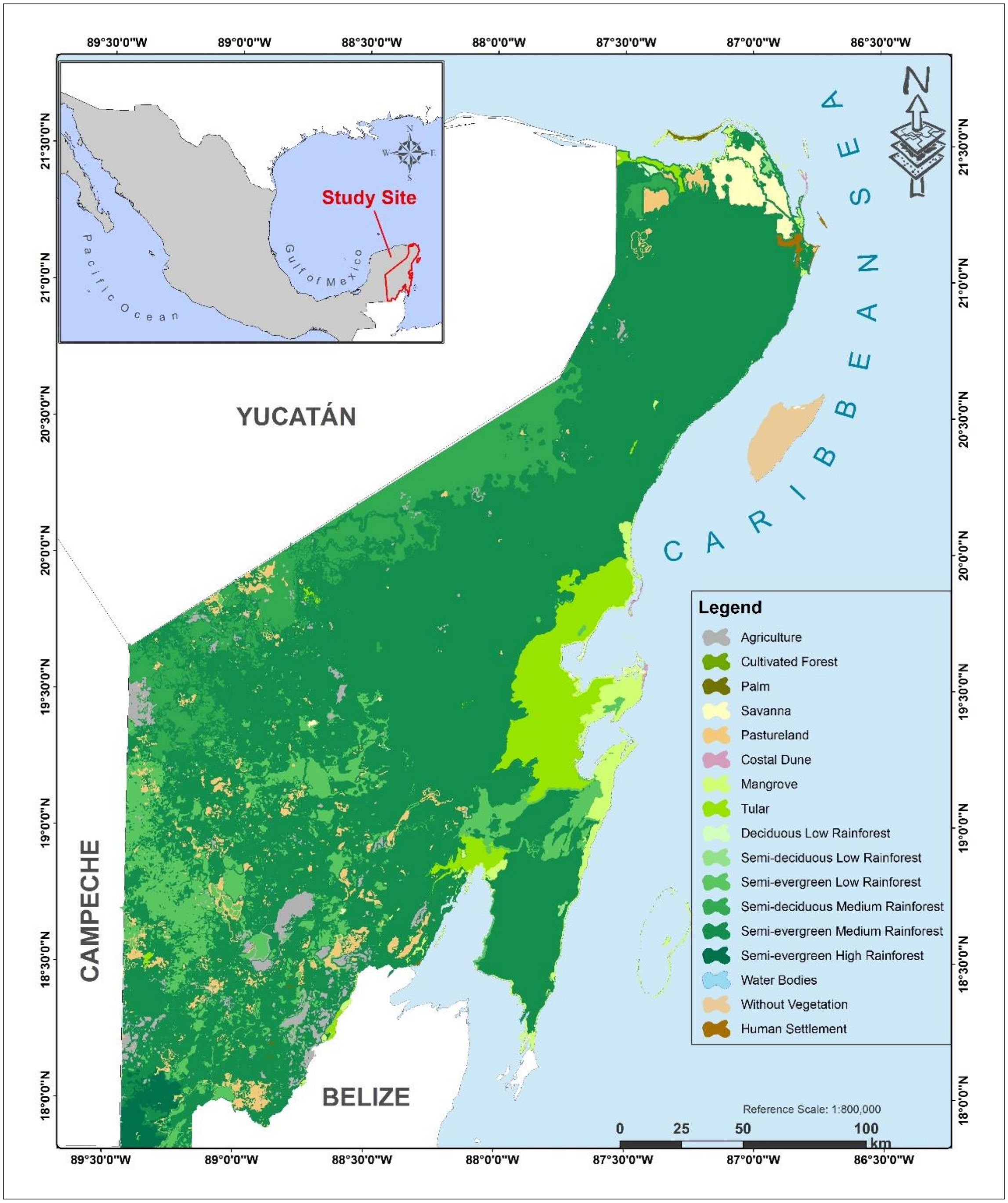

Figure 8. *Land uses in State of Quintana Roo (own elaboration, data obtained from Fragoso-Servón, 2015; INEGI, 2013b)*

3.7 Human Land-use and Socio-economic Factors

In the state of Quintana Roo, there are about 1,325,000 inhabitants (INEGI, 2010) and they are distributed among ten municipalities: Isla Mujeres, Lázaro Cárdenas, Benito Juárez, Solidaridad, Cozumel, Tulum, Felipe Carrillo Puerto, José María Morelos, Bacalar, and Othón P. Blanco.

According to the SAGARPA (2012) cited by Fragoso-Servón (2015), agricultural land occupies 83,409.86 ha and provides an income of 494,089.69 thousand Mexican pesos. Agricultural production is located primarily in the south, east, and center of the state. From the total cropland, 98% of the area corresponds to temporary crops which include grain maize (62.00%), sugarcane (19.40%), corn (6.70%), and orange (2.90%). Other less cultivated crops are beans, sweet pepper, sorghum, coconut, banana, lemon, papaya, pineapple, pitahaya, yam, and melon.

Regarding agroforestry, the municipalities Felipe Carrillo Puerto, Othón P. Blanco, and José María Morelos produce timber (cedar, mahogany, etc.) and chicle (natural gum; non-timber) for exportation. For harvest and restoration purposes, community land owners protect and produce Chaká (*Bursera simaruba*), Chechem (*Metopium brownei*), Sac’chaká (*Dendropanax arboreus*), Jobo (*Spondias mombin*), Chicozapote (*Manilkara zapota*), Amapola (*Pseudobomax elipticum*), Ramón (*Brosimum alicastrum*), Tzalam (*Lysiloma latisiliquum*), Machiché (*Lonchocarpus castilloi*), and many more. From the data recorded from INEGI (2011), the state obtained a total volume of 94,271 m^3 of wood in forest production; 20% of it corresponds to precious timber which has a value of 58,730,000 thousand of Mexican pesos.

CHAPTER 4 MATERIALS AND METHODS

4.1 Methodological Framework

The research method is divided into five sections, each categorized by a given color in the flow diagram (Figure 9). Brown is the research focus and referred to the backbone of the entire sampling. Blue is the geophysical data obtained from the soil and the relief data processed by Fragoso-Servón (2015). Light-green is the land use data that is classified by INEGI (2013b). In this study, only natural vegetation was selected since agricultural land, and cultivated forest are land use under anthropogenic intervention, which contains a high variability of soil carbon content depending on the land management. Sea green is the vegetation and the soil reference classified by FAO (2014), Fragoso-Servón (2015), INEGI (2013b), (2013a), Miranda and Hernández (1963), and Rzedowski (2006). Gold is the soil analysis performed to compare soil properties and the soil carbon. The soil properties examined include soil color, soil texture, pH, conductivity, bulk density, and rock fragments; while soil carbon includes TSC, SOC, and SIC. For the soil carbon, only SIC did not have two or more samples with the same combination. As shown in Appendix A, the ANOVA for repeated measures demonstrates that the result among the repetitions was insignificant; hence, it is assumed that the value of SIC estimated has a similar confidence interval. The last three outputs (orange, dark green and purple) are the data analysis relating vegetation, soil properties, and soil carbon.

The soil carbon was not estimated by BSI, NDVI, or Vis-NIR; rather, it was measured using traditional methods since the State of Quintana Roo has unique biogeomorphoedaphic characteristics. The TSC was conducted using the loss-on-ignition method (LOI) (Wang et al., 2012), modifying the combustion time to 30 minutes. A time test was performed by increasing the hours of combustion (30 min, 1 h, 2 h, and 4 h) using three different soils with high, medium, and low SOM. The result (Appendix B) showed that the carbon content had minor differences with an average standard deviation of 0.03 g out of 1 g of soil. For SOC, the Walkley-Black method (Gelman et al., 2011; SEMARNAT, 2000) was implemented using diphenylamine as an indicator. SIC was quantified using the acid dissolution method (SEMARNAT, 2000) since the geologic platform of the region is formed from sedimentary rocks which contain high content of $CaCO_3$. Lastly, the soil carbon distribution was extracted similarly to the research done by Wu et al. (2009).

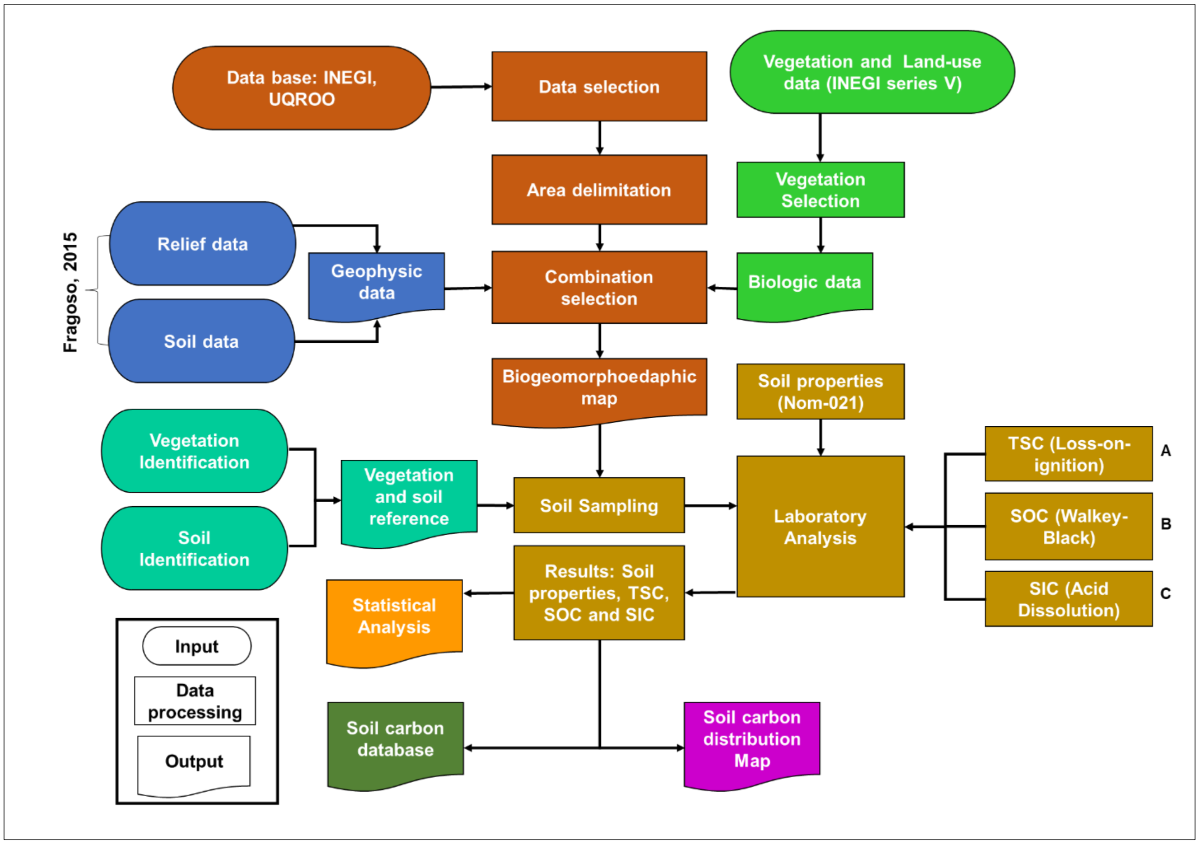

Figure 9. *Methodologic Flow Diagram. Brown: Data selection and area delimitation, Light Green: Vegetation and Land use, Blue: Geophysical data, Sea Green: Vegetation and Soil Reference, Gold: Soil properties and soil carbon estimation, Orange: Statistical Analysis (Descriptive Statistics, Principal component analysis, Correlation of Pearson, Agglomerative hierarchical clustering), Dark Green: Soil carbon database, and Purple: Soil Carbon Distribution Map (Own elaboration).*

4.2 Selection of Soil Sampling Site (Area Delimitation)

Sampling sites were identified using information of vegetation (INEGI, 2013b) and soil (Fragoso-Servón, 2015) with a scale of 1: 250,000 for land use and 1:50,000 for soil types. A matrix of vegetation and soil was done to identify possible combinations. In total, only 38 combinations were used to conduct the research. The sampling method is performed in a purposive manner using the soil and land use map extracted from the doctorate thesis of Fragoso-Servón (2015). Sampling points were selected by the accessibility of streets or roads to facilitate sample extraction.

4.3 Extraction of samples

The sampling unit was extracted from a location where the vegetation was well conserved. Each combination was considered as a sampling point and the soil samples were collected at a depth of 30 cm or at its maximum depth for soils shallower than 30 cm (i.e. Leptosols). Characteristics of the sampling site were recorded along with the geographic coordinates. The samples were sealed and labeled, and ensured with a minimum weight of 500g according to IPCC methodologies for laboratory analysis (Department of the Environment, 2014; Stolbovoy et al., 2007).

4.4 Sample Preparation

After extraction, samples were left in the laboratory to dry with an environmental condition controlled in the laboratory. In the preparation of the samples, rocks and other materials with a size above 3 cm were omitted. To obtain the apparent density, samples were dried at a temperature of 105^0C throughout the night and the bulk density was estimated using the formula (mass/volume). Soil properties such as pH, conductivity, color, and texture were also estimated according to Mexican Nom-021 (SEMARNAT, 2000).

4.5 Modified Loss-on-ignition (LOI) for TSC

The loss-on-ignition was used to determine the TSC. Three repetitions were used for each sample. The crucibles were dried at 800^0C for five minutes and then left in a desiccator. After cooling off, 1 g of soil was put into the crucible and heated in the furnace at the same temperature for 30 minutes. For every 5 minutes, the furnace was opened for oxygen circulation to ensure complete combustion. After 30 minutes of heat combustion, the crucibles were cooled in the desiccator for an hour and then the soil total carbon was estimated from the weight loss (Chen et al., 2015; Wang et al., 2012).

4.6 Walkley-Black Method (WB) for SOC

The mechanism of this method was to oxidize the organic carbon of the samples into

CO_2 by excess oxidants, $K_2Cr_2O_7$, then with the use of $FeSO_4$ to titrate the remaining $Cr_2O_7^{-2}$, and the organic carbon content to estimate the amount of $Cr_2O_7^{-2}$ consumed during the reaction. A soil sample (0.25g) was treated with 10ml of 0.166 M $K_2Cr_2O_7$ and 20 ml of concentrated H_2SO_4 for 30 min in 500ml Erlenmeyer flask and then mixed with 200 ml of deionized water and 5 ml H_3PO_4. Five to ten droplets of diphenylamine were added to the solution as an indicator. The unreacted $K_2Cr_2O_7$ was determined by titrating with 1 M $FeSO_4$. The SOC content was calculated from the difference between the amount of $FeSO_4$ used in a blank and a soil solution (Chen et al., 2015; Gelman et al., 2011; SEMARNAT, 2000).

The following is the formula used to determine the percentage of organic carbon (OC):

$$OC\,\% = \left[\frac{B-S}{m}\right](N)(mcf)$$

where N is the exact normality of $FeSO_4$, B is the volume of $FeSO_4$ used in the blank, S is the volume of $FeSO_4$ used in the sample, m is the mass of the sample in gram used in the analysis, and mcf is the humidity factor of correction (0.39). During the process of $FeSO_4$ titration, the color changed from reddish brown to blue-green.

Chemical Reactions:

$$2Cr_2O_7^{2-} + 3C + 16H^+ \rightarrow 4Cr^{3-} + 3CO_2 + 8H_2O$$

$$Cr_2O_7^{2-} + 6Fe^{2+} + 14H^+ \rightarrow 2Cr^{3-} + 6Fe^{3+} + 7H_2O$$

To calculate the percentage of organic matter (OM) present in the soil, the following formula was applied.

$$OM\,\% = OC\,\% * 1.724$$

4.7 Acid Dissolution Method (AD) for SIC

The mechanism of the AD method is to infer the inorganic carbon from the percentage of $CaCO_3$ estimated. Firstly, 5 g of soil was placed on a 250 ml beaker and 100 ml of 0.5 M HCL was mixed with the soil. Occasional stirring was applied during an hour. After the settlement of the sediment, 20 ml of the solution was taken out and inserted in 250 ml Erlenmeyer flask along with10 droplets of bromothymol blue (indicator). The $CaCO_3$ content was calculated from the difference between the amount of sodium hydroxide (NaOH) used in a blank and a soil solution during titration.

The following is the formula used to determine the percentage of calcium carbonate ($CaCO_3$):

$$CaCO_3\,\% = (B - M)5$$

where B is the volume of NaOH used in the blank and S is the volume of NaOH used in the sample. During the process of NaOH titration, the color changed from orange to green-blue.

To calculate the percentage of inorganic carbon present in $CaCO_3$, the following formula was applied:

$$C\,\% = CaCO_3\,\% * 0.1$$

4.8 Statistics Analysis (XLSTAT)

The relationship between the concentration of soil carbon with the soil properties was observed using Descriptive Statistics, ANOVA, Principal component analysis, Correlation of Pearson, Agglomerative hierarchical clustering (Ward’s method), and Olmstead-Tukey corner test (Berry et al., 2014; Jongman and Van Tongeren, 2005; Steel and Torrie, 1992).

4.9 Distribution of soil carbon

The concentration of total carbon, organic, and inorganic of each sampling site was calculated using the following formula (Stolbovoy et al., 2007):

$$\sum_{i=1}^{n} (BD * TH * \left[1 - \frac{CR}{100}\right]) * C$$

where BD is the bulk density, TH is the thickness of the soil extracted, CR is the rock fragment materials and C is the percentage of carbon in the soil.

The soil carbon distribution is projected with ArcMap 10.5. Using the data processed, the estimation of carbon captured was analyzed by associating it with soil properties, vegetation, climate, and geomorphology of the area.

CHAPTER 5 RESULTS AND DISCUSSION

5.1 Soil carbon content related to vegetation characteristics, and soil properties

In total, there were 44 samples, some of them at sites with same soil vegetal combination; therefore, those samples were averaged and only 38 different combinations were extracted (Appendix C). After considering the factors contributing to the soil carbon content, the combination coastal dune vegetation-Arenosol holds the highest total carbon density of 1256.22 Mg C ha^{-1}, possibly due to the biogenic origin of sands in the Mexican Caribbean (Pereira-Corona, 2006), while the combination semi-deciduous low rainforest-Leptosol portrays the lowest soil carbon content (53.75 Mg C ha^{-1}). For soil organic carbon by Walkley-Black (SOCw), the combination flooded low rainforest-Gleysol reports the highest (195.37 Mg C ha^{-1}) and coastal dune vegetation-Arenosol has the lowest (8.97 Mg C ha^{-1}). Lastly, the combination coastal dune vegetation-Arenosol presents the highest SIC of 229.78 Mg C ha^{-1} while semi-evergreen medium rainforest-Cambisol, and Semi-evergreen medium rainforest -Luvisol capture the lowest (0.00 Mg C ha^{-1}).

It is knowable that the vegetation and soil combination (Appendix C, Table 11) associate with each other; although having the same soil type but the content of CO_2 captured is dissimilar. This can be explained by the vegetation characteristics which is one of the factors that influences the soil carbon content. For instance, Leptosol in three different vegetation forms: Semi-deciduous low rainforest (53.75 Mg C ha^{-1}), Semi-evergreen medium rainforest (138.05 Mg C ha^{-1}), and Semi-deciduous medium rainforest (216.83 Mg C ha^{-1}), each presents unalike TSC content. The soil carbon density of Semi-deciduous medium rainforest is the highest while semi-deciduous low rainforest is the lowest. One of the factors that can shed some light on such differences is the vegetation composition. As mentioned (INEGI, 2015a), 25 to 50% of the species loses leaves in semi-evergreen forest, and 50 to 75% of the species loses leaves in semi-deciduous. In addition, the average height of the forest plays an important role since it is directly proportional to the vegetation coverage.

When the data is grouped by soil type (Appendix D), the analysis of agglomerative hierarchical clustering portrays some similarity among samples and forms three classification groups (Figure 10). The first group (Phaeozem, Luvisol, Kastanozem, Gleysol, Vertisol, Cambisol, and Nitisol) are soils with low carbonate content with a TSC between 25 to 36%. The second group comprises latter soils (Regosol, Arenosol, and Solonchak) with high concentration of carbonates, and low organic matter ranging from 37 to 42% of TSC. The last group (Leptosol, Fluvisol, and Histosol) are soils with large quantities of organic matter with TSC fluctuating from 41 to 45%. In short, soil group one has the least TSC percentage stored, followed by group two, and group three. The group classification is altered by the high variance of soil texture and rock fragments as shown in Appendix D, Table 14.

For vegetation, the agglomerative hierarchical clustering (Figure 11) shows that the three categories formed from soil carbon content and soil properties are grouped because of the high variance of the soil texture. From here, it can be explained that cluster two and three are wetlands vegetation. In contrast, cluster one is rainforest. In the case of marshland vegetation, it is put under the first classification because during dry season this type of vegetation is usually identified as low rainforest, while during the wet season it is referred to as wetland vegetation. Therefore, the dissimilarity distance between marshland vegetation and other vegetation in cluster one is wider compared to the distance differences among rainforests (Cluster one).

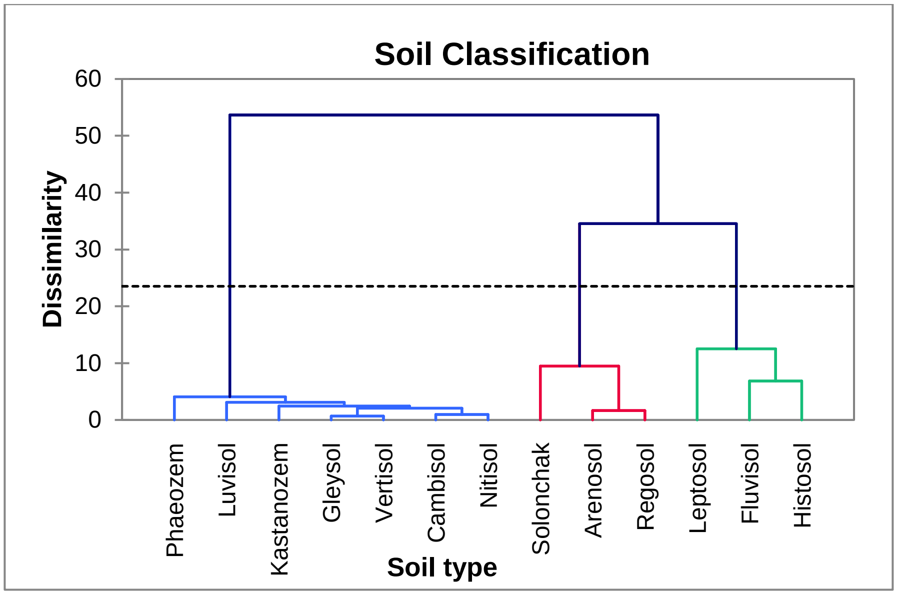

Figure 10. *Soil classification. First group: color-light blue; second group: color-red; third group: color-green (Own elaboration).*

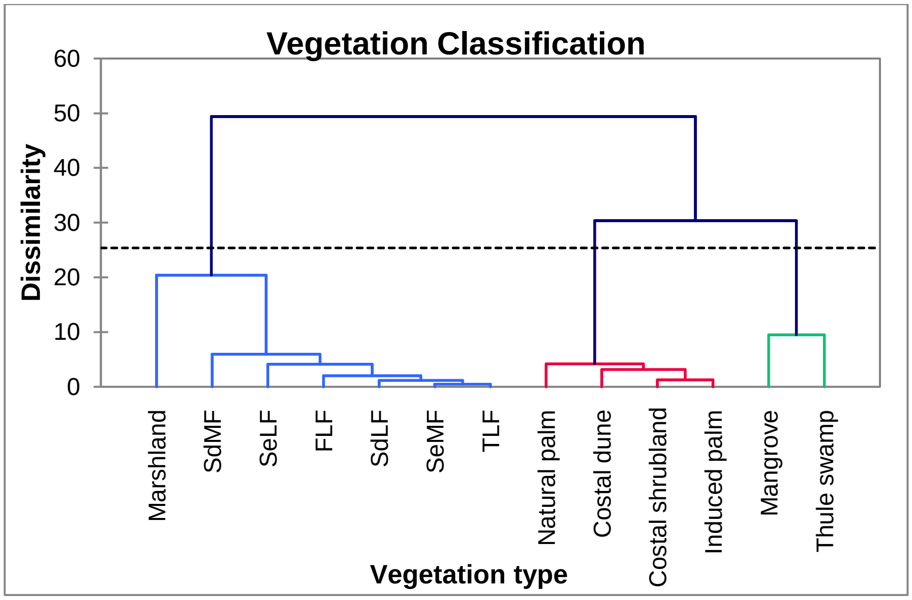

Figure 11. *Vegetation classification. (FLF = Flooded low rainforest, SdLF = Semi-deciduous low rainforest, SdMF = Semi-deciduous medium rainforest, SeLF = Semi-evergreen low rainforest, SeMF = Semi-evergreen medium rainforest, and TLF = Thorny low rainforest) Groups: color-light blue (1), color-red (2), color-green (3) (Own elaboration).*

According to the principal component analysis (Figure 12), the percentage of sand contributes to a slightly basic pH and determines the percentage of inorganic carbon in forms of carbonate content, while the amount of silt and rocks fragments influence the concentration of organic carbon in forms of humus concentration. Lastly, the TSC is strongly associated with SOCw and SIC. Similarly, the Pearson correlation matrix (Appendix E, Table 15) shows the same result, projecting a positive relationship between carbonates, pH, and sand concentration. Unlikely, bulk density and clay content are factors apparently limiting soil carbon sequestration. Thus, soil carbon storage (Appendix E, Table 16) have two main components, the inorganic matrix (F1), and the organic one (F2).

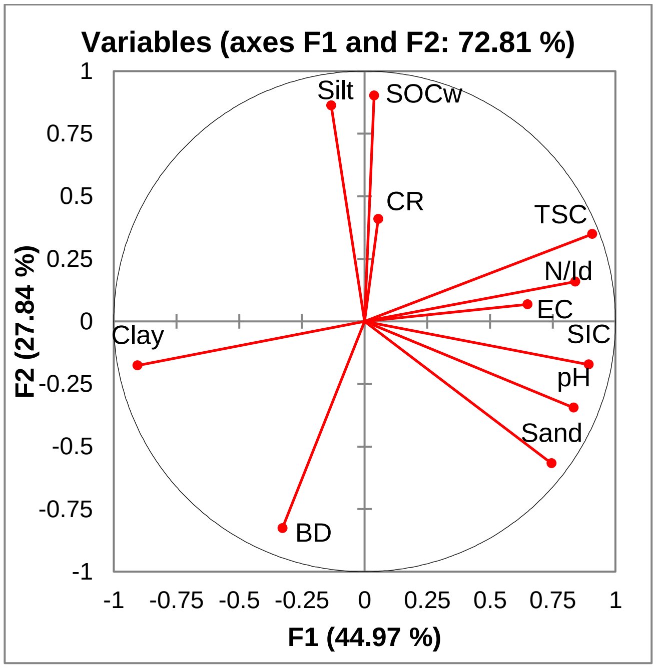

Figure 12. *Principal component analysis for F1 and F2. These two factors represent 72.81% of importance in the correlation among all variables (TSC = total soil carbon, SOCw = soil organic carbon by Walkley-Black, SIC = soil inorganic carbon, N/Id = unidentified content, EC = electrical conductivity, BD = bulk density, and CR = rock fragments) (Own elaboration).*

5.2 Soil carbon density associated with biogeomorphoedaphic factors

After calculating the average of soil carbon density per soil type, Solonchak is the soil with the highest TSC (1,246 Mg C ha^{-1}), and Leptosol the soil with the lowest (347 Mg C ha^{-1}) (Figure 13). For SOCw, the soil carbon density ranges from 34 Mg C ha^{-1} to 155 Mg C ha^{-1} (Solonchak and Nitisol) (Figure 14). For SIC, Arenosol is the densest (173 Mg C ha^{-1}), and Luvisol is the least (5 Mg C ha^{-1}) (Figure 15).

Conversely, the soil capacity has a different value. Due to the surface area occupied by each soil type, the Olmstead-Tukey corner test (Figure 16, 17, and 18) shows that Leptosol, Gleysol, and Phaeozem are the most predominant while Vertisol is the most abundant. The rarest soils are Fluvisol, Regosol, Kastanozem, Histosol, and Nitisol due to tropical karstic features of Quintana Roo (Fragoso-Servón, 2015). The others are also classified under rare soils but they are around the corner of abundant or near the intersection (average) between frequency, and soil capacity.

The soil with the highest TSC soil capacity is Leptosol (852 MtC) and the least is Fluvisol (0.19 MtC) (Figure 16). For SOC, Leptosol (160 MtC), and Fluvisol (0.03 MtC) encounter in the same ranking as the TSC soil capacity (Figure 17). For SIC, Gleysol is the highest (72 MtC), and Fluvisol is the lowest (0.01 MtC) (Figure 18) (an overview of all data can be observed in Appendix F).

The soil distribution map (Figure 19, 20, and 21) shows that soil carbon is denser at the physiographic provinces: Lower coast of Quintana Roo, and Karst and Ridge of Campeche. Similar effects are shown in SOC density distribution. For SIC, the diffusion is clearly shown at the upper part of Quintana Roo, Sian Ka'an biosphere reserve, and around the site that contains water bodies. Therefore, relating soil carbon distribution and landscape characteristics, it is observed that SOC content is highly bound with warm subhumid, medium humidity climate (Aw_1) (INEGI, 2008a), the alluvial accumulation of organic matter caused by the topographical relief (INEGI, 2001), and the soil type (Phaeozem and Vertisol) (Fragoso-Servón, 2015), while SIC concentration is characterized by the carbonate weathering, and illuvial erosion of materials.

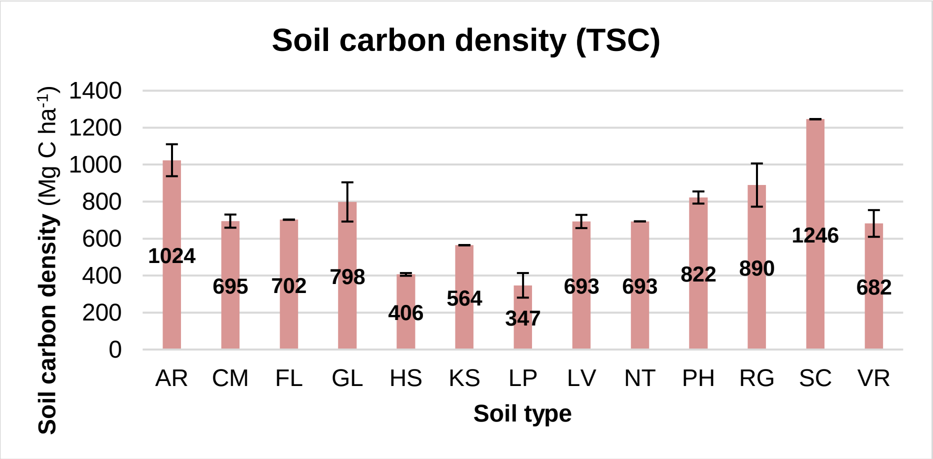

Figure 13. *Soil carbon density (TSC). The chart demonstrates the average soil carbon, and standard error for each Soil type (AR = Arenosol, CM = Cambisol, FL = Fluvisol, GL = Gleysol, HS = Histosol,*

KS = Kastanozem, LP = Leptosol, LV = Luvisol, NT = Nitisol, PH = Phaeozem, RG = Regosol, SC = Solonchak, and VR = Vertisol) (Own elaboration).

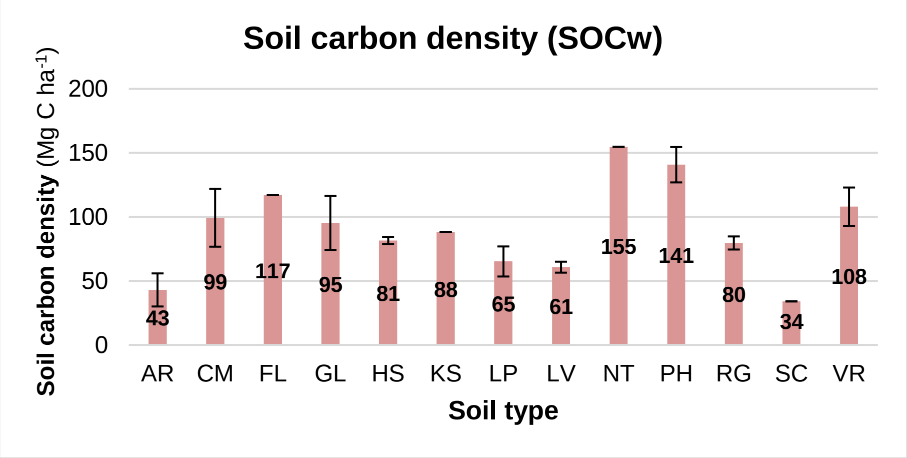

Figure 14. *Soil carbon density (SOCw). The chart demonstrates the average soil carbon, and standard error for each soil type (Own elaboration).*

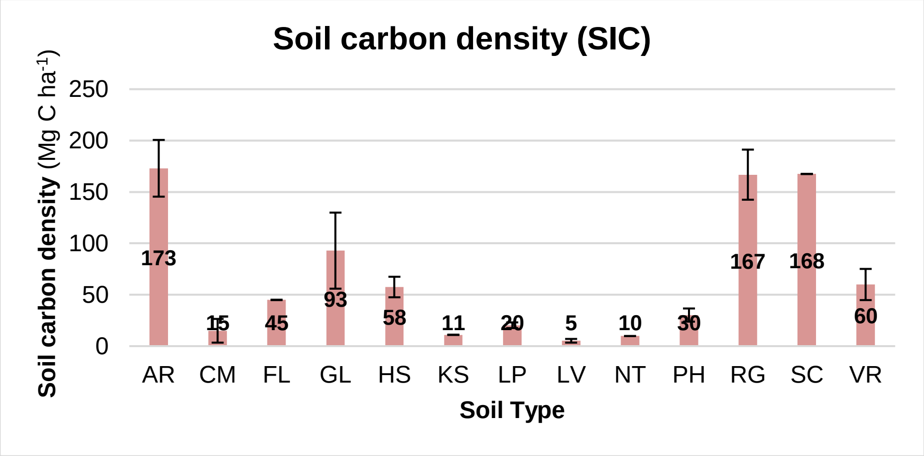

Figure 15. *Soil carbon density (SIC). The chart demonstrates the average soil carbon, and standard error for each soil type (Own elaboration).*

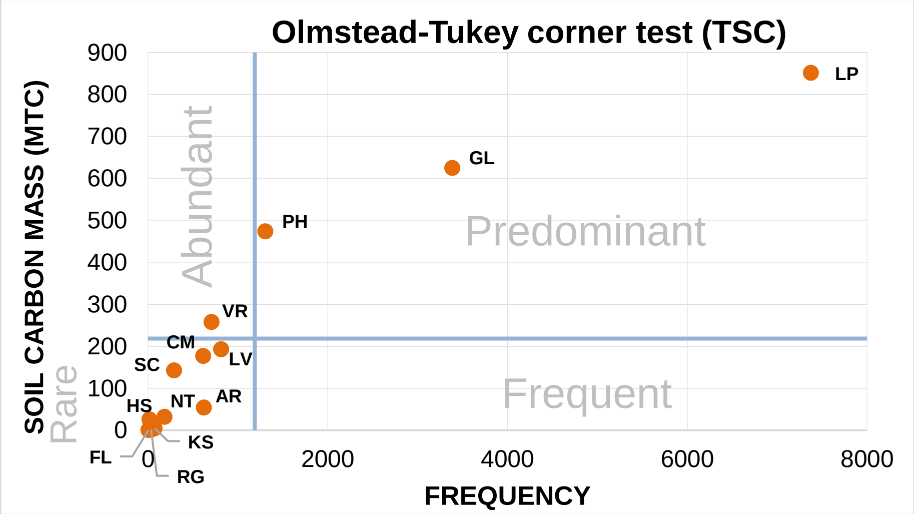

Figure 16. *Olmstead-Tukey corner test (TSC). The analysis demonstrates the category (abundant, predominant, frequent, or rare) in which the soil type falls under according to its soil carbon capacity and frequency (Own elaboration).*

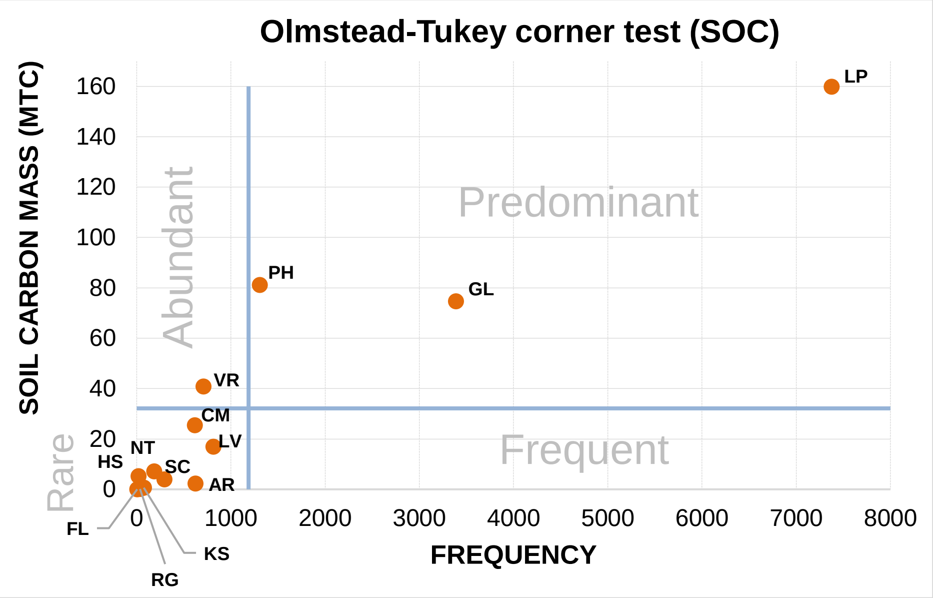

Figure 17. *Olmstead-Tukey corner test (SOC). The analysis demonstrates the category (abundant, predominant, frequent, or rare) in which the soil type falls under according to its soil carbon capacity, and frequency (Own elaboration).*

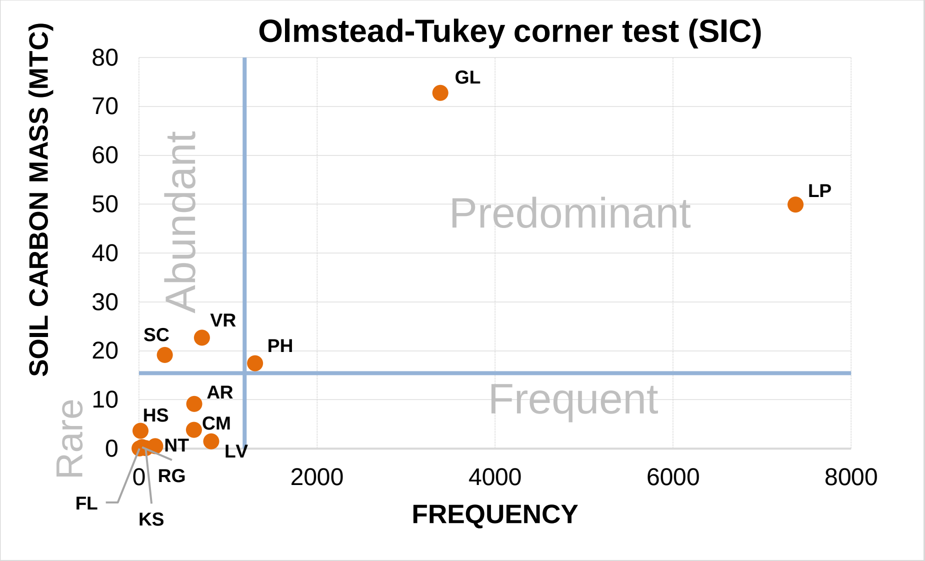

Figure 18. *Olmstead-Tukey corner test (SIC). The analysis demonstrates the category (abundant, predominant, frequent, or rare) in which the soil type falls under according to its soil carbon capacity, and frequency (Own elaboration).*

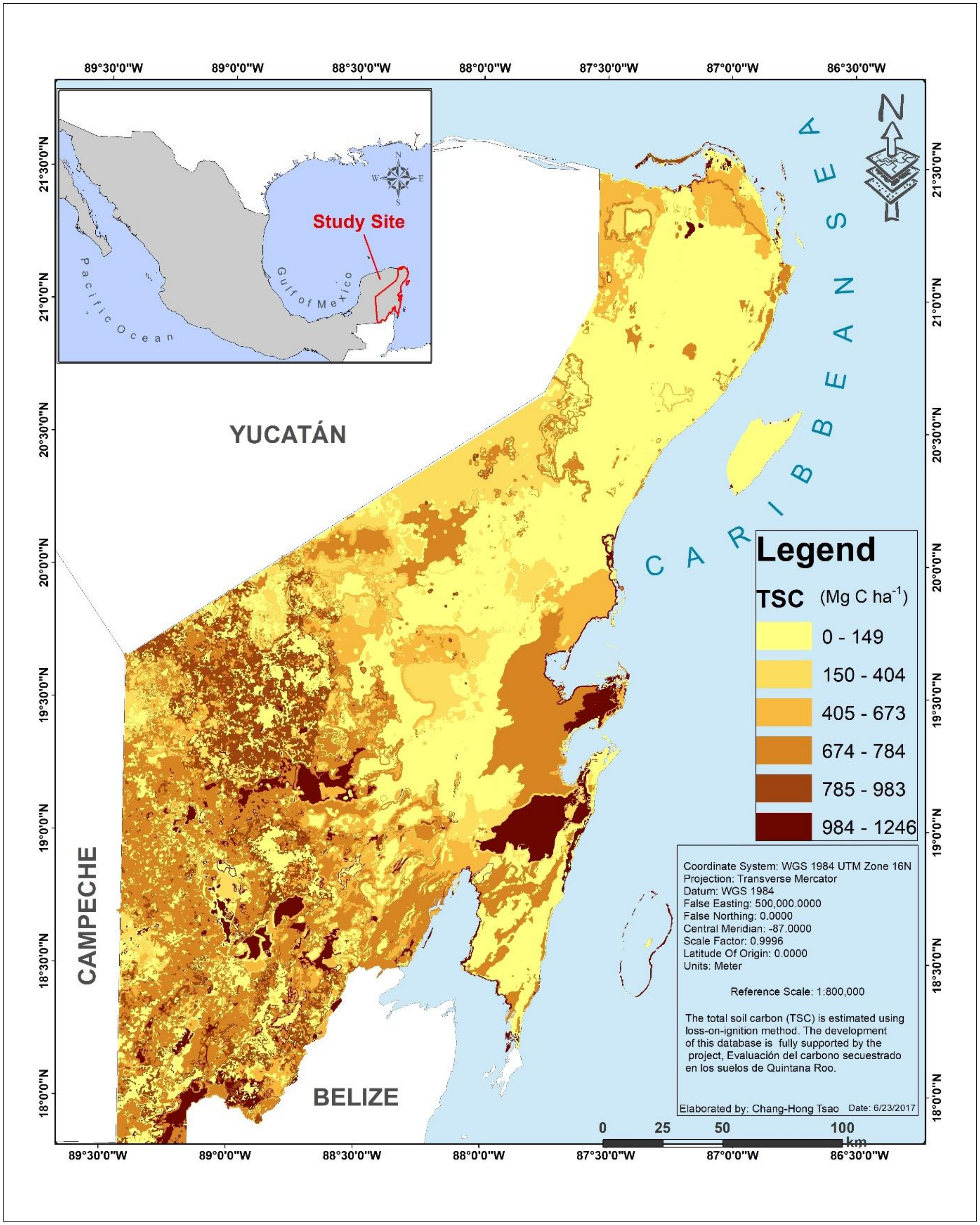

Figure 19. *Total soil carbon distribution in the State of Quintana Roo. The map demonstrates the soil carbon density of TSC distributed across the entire State of Quintana Roo (Own elaboration).*

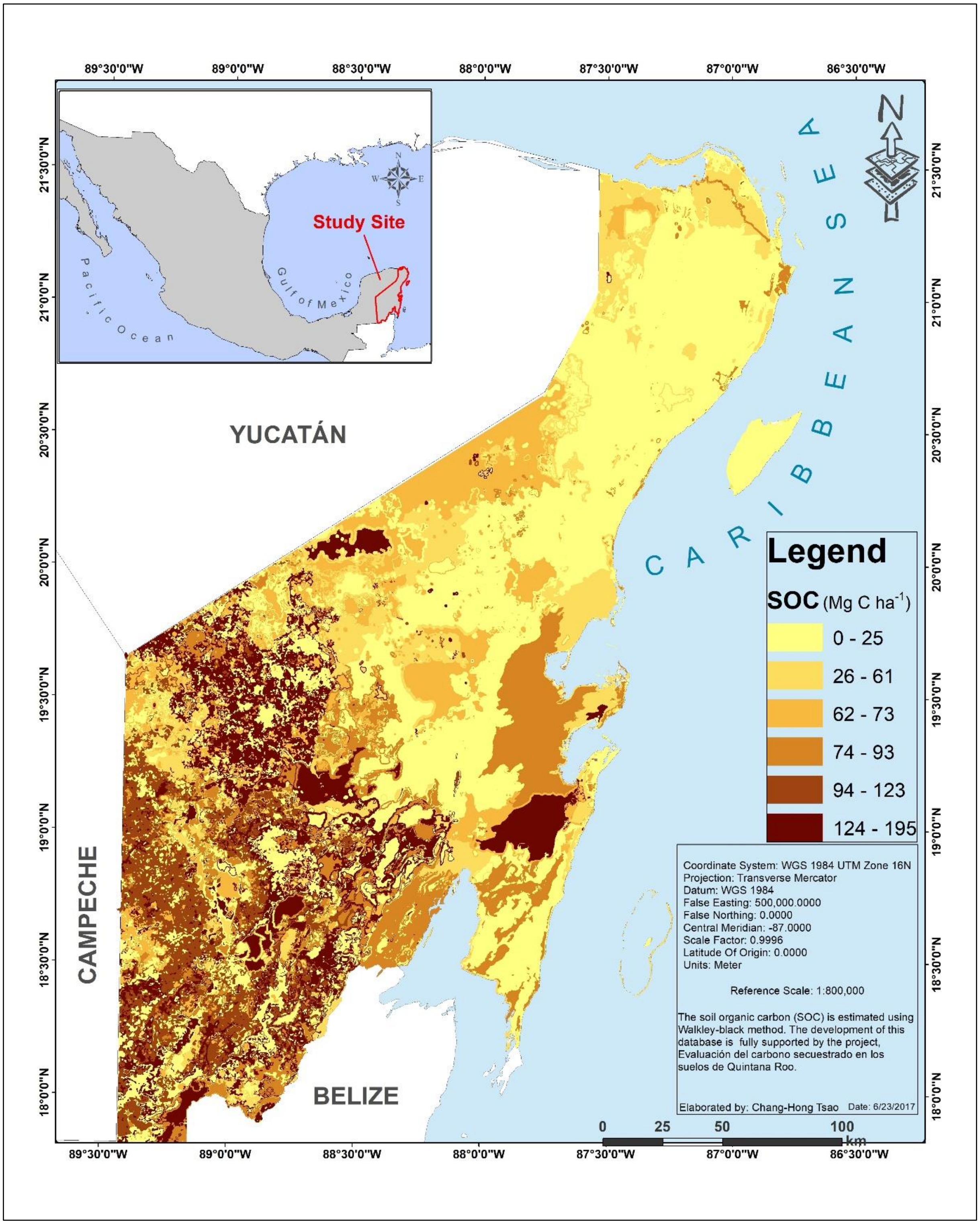

Figure 20. *Soil organic carbon distribution in the State of Quintana Roo. The map demonstrates the soil carbon density of SOC distributed across the entire State of Quintana Roo (Own elaboration).*

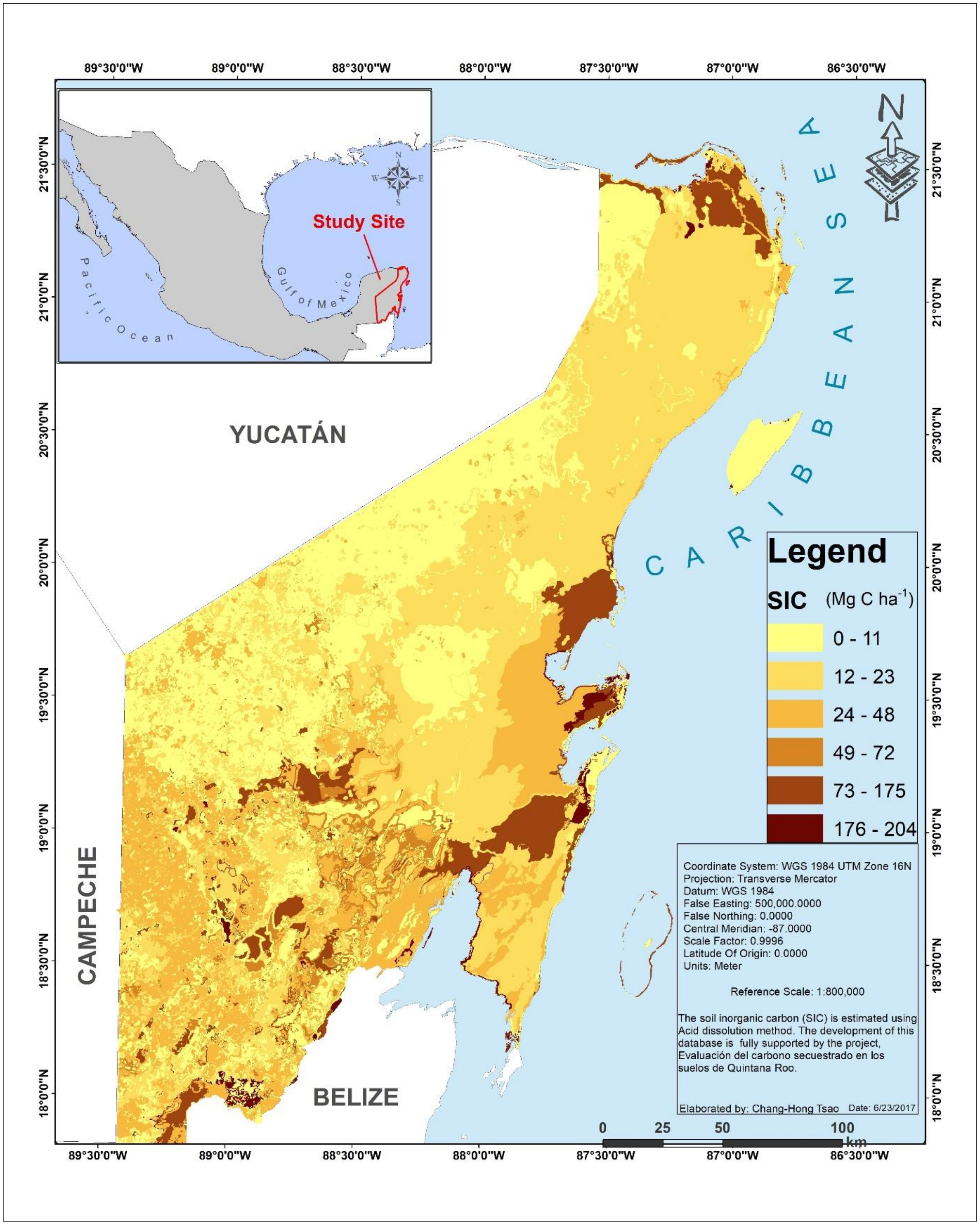

Figure 21. *Soil inorganic carbon distribution in the State of Quintana Roo. The map demonstrates the soil carbon density of SIC distributed across the entire State of Quintana Roo (Own elaboration).*

5.3 Comparison and Explanation of Data

From the data reported by INEGI (2013a), soil carbon is extracted from the combination of land use and soils with maximum depth, without differentiating the type of tropical forest (rainforest). However, in general, the data of soil carbon and soil properties contain similar values with exception of some combinations. Mangrove-Leptosol is one of the combination that contains dissimilar values (SOCw = 2.3% and SIC = 11.7%). On the other hand, Rainforest-Leptosol shows an intimate value (SOCw = 6.30% and SIC = 4.42%). The variation of data can be attributed by differences in sampling procedures of INEGI and those used in this project. By comparing the soil carbon of the first 30 cm extracted from Encrucijada Biosphere Reserve, State of Chiapas, Mexico (Adame et al., 2015), the average content of SOC is higher (16.74%) than the study area (4.86%); one of the factors can be the accumulation of ashes from the volcanic eruption in 1902 and the other can be the methodology used to estimate SOC (Costech Elemental Combustion System 4010). This information can be compared with Table 10, Appendix C. Apart from SOCw and SIC estimated, an unidentified (N/Id) carbon source was also calculated. Part of this content (N/Id) can be assumed as humin because when averaging SOCw and N/Id the value (19.89%) is very closely related to the value (16.74%) estimated from the case study of Encrucijada Biosphere Reserve.

According to Tadini et al. (2015), humin represents 20 to 50 % of humic substances. It is closely associated with inorganic soil colloids, swelling clays, and iron compounds (Li et al., 2015) and cannot be extracted by dilute base or acid (Schnitzer and Khan, 1978), which means the Walkley-Black method for SOC is less precise since it can only decompose unrestricted humic acid, and fulvic acid completely. On the other hand, loss-on-ignition method provides more accurate SOC since it can decompose humin completely when clay contents are low in the soil (Blume et al., 2016b). Hence, it can be inferred that only methods that can create high-temperature combustion are able to totally decompose humic substances. Due to the fact of that, the loss-on-ignition method (800ºC) used in the study can fully estimate the TSC.

By relating, natural vegetation soil carbon with agricultural soil carbon, INEGI (2013a) states that croplands contain an average of 0.8% SOCw. This value is far lower than the natural vegetation (4.79%). In addition, the minimum value of cropland (0.10%) demonstrates a large soil carbon loss. While the maximum value (8.20%) is found in Temporal agriculture-Leptosol where less soil carbon loss is shown. According to INEGI (2015a), Temporal agriculture depends on rain water and it includes seasonal crops, fruticulture, and crops cultivated under natural vegetation. This may be a factor explaining higher SOC content retained by this Agriculture type and Soil. In short, as mentioned by Stene (2007), the change in land use from cropland to forestry can improve SOC stock. Similarly, the data represented by Tate et al. (2005) explains that natural vegetation stores higher SOC than cropland.

According to INEGI (2015b), research conducted by UNDP, the entire territory (196,437,500 ha) of Mexico stores 6,150 MtC (SOC), and the average soil carbon density is 32.60 Mg C ha^{-1}. However, the tropical forest (32,059,162 ha) with 16% of the total surface area (Mexico) amount to 2,597 MtC (42%) and contains approximately 81.00 Mg C ha^{-1}. In the study, Quintana Roo soil (5,084,300 ha) captures 418 MtC which represents about 16% of the amount stored from the entire tropical forest in Mexico. The soil organic carbon map estimated by Cruz-Cárdenas et al. (2014) also shows similar distribution features than that of INEGI. Relating the soil carbon map (Cruz-Cárdenas et al., 2014) with the vegetation carbon map (Murray-Tortarolo et al., 2016), the tropical forest contains the highest carbon density. Hence, it is undeniable that tropical forests have high SOC sequestration capacity.

Lastly, observing the FAO topsoil SOC density map (Hiederer and Köchy, 2011), the value 75 to 150 Mg C ha^{-1} is similar to the average (82.00 Mg C ha^{-1}) obtained in the study. In comparison with the carbon content of tropical soil (60%) in the Cerrado biome of Brazil (da Silva et al., 2008), the study area has a lower TSC value (35%). The large difference in value can be affected by the soil type and vegetation which is not mentioned in the study. Due to the scarcity of SIC research, the SIC result of Quintana Roo is compared with the monsoonal tropical–subtropical soils of China. According to the data reported by Wu et al. (2009), the value of Regosol (19.10 Mg C ha^{-1}) and Solonchak (19.00 Mg C ha^{-1}) is far away from the content in the study area (Regosol = 166.83 Mg C ha^{-1} and Solonchak = 167.51 Mg C ha^{-1}). On the other side, soils such as Leptosol (6.10 Mg C ha^{-1}), Cambisol (0.90 Mg C ha^{-1}), and Luvisol (2.00 Mg C ha^{-1}) present a closer interval; however, the State of Quintana Roo still has a denser soil inorganic carbon stock (Appendix F, Table 17). Regardless of similar tropical climate, the differences in geology, geomorphology, vegetation and other environmental factors contribute to a distinct value of SIC.

CHAPTER 6 GENERAL CONCLUSIONS AND FUTURE WORK

6.1 Research conclusion

The presented results show that the stated hypothesis is true. There exists a relationship between land use - soil type pairs with carbon sequestration due to distinct vegetation characteristics and soil properties. As shown in the carbon distribution map, the soil carbon does not depend on a specific variable. Nevertheless, it considers all factors such as mineralogy, depth, stoniness, bulk density, porosity, biomass coverage, biomass composition, precipitation, temperature, land relief, geologic parental rock formation, geomorphology, and fauna. In short, it can be grouped into abiotic and biotic attributes. The carbon flux and storage is altered by these physical, chemical, and biological interactions.

The amount of carbonates in the soil is associated with the sedimentary origin of the parent material. The slight alkalinity caused by the weathering of parent rocks regulates the pH to a neutral value when encountering with the organic acids.

In the carbon distribution map, the physiographical province, Karst and Ridge of Campeche contains the major soil organic carbon density due to the stair-like structure of the relief in the southeast of the territory which supports the accumulation of organic matter due to the alluvial phenomenon and consequently deeper soils. On the other hand, sandy soils on the coast predominate the SIC content since the sea waves support the formation of beaches largely formed of debris of carbonaceous structures of marine organisms. However, vegetation is the key point because it prevents soil erosion and contributes to soil carbon conservation, pushing the enrichment of those arid and inorganic substrates.

In addition, sampling statistics have shown that natural vegetation has denser soil carbon content than agricultural land. Even though cropland soils were not sampled, but compared with results from INEGI and other sources, result of other researchers demonstrates the same principle.

6.2 Future Challenges

As viewed in many studies, each country has their own vegetation and soil classification. This establishes a barrier in the comparison of data. For instance, Lal (2004) reported global soil carbon categorized using Twelve Soil Taxonomy. Others, such as Wu et al. (2009) uses local soil taxonomy. It would be great if soil carbon studies are classified using World reference base.

For future research, other environmental components can also be included in soil carbon estimation such as altitude, radiation, wind, soil humidity, microbial activity, etc. The use of remote sensing must be soil sampling calibrated and then combined to ensure more accurate soil carbon distribution studies. A model of soil carbon for each climatic and geomorphologic region can be established to better compare data. This will require more sample repetitions and methods experiment; which includes the identification of the N/Id fraction obtained from the difference between TSC and the sum of SOCw, and SIC in the study.

Governmental decision making can also use similar land evaluation and soil protection scheme proposed by Blume et al. (2016c). This comprises soil assessment and evaluation for taxing and land use. Since ecosystem services are assigned with a monetary value, a complex model should be used to place a less biased pricing to it.

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APPENDIXES

Appendix A: ANOVA for repeated measures

Table 5: ANOVA for repeated measures (TSC)

Source	DF	Sum of squares	Mean squares	F	Pr > F	Adj. Pr>F G-G	Adj. Pr>F H-F
Repetition	2	0.006	0.003	10.025	< 0.0001	0.000	0.000
Error	86	0.025	0.000				

(Own Elaboration)

Table 6: Repetition / Tukey (HSD) with a confidence interval of 95% (TSC)

Contrast	Difference	Standardized difference	Critical value	Pr > Diff	Significant
Repetition-II vs Repetition-III	0.014	0.682	2.371	0.774	No
Repetition-II vs Repetition-I	0.014	0.687	2.371	0.772	No
Repetition-I vs Repetition-III	0.000	0.005	2.371	1.000	No
Tukey's d critical value:			3.353		

(Own Elaboration)

Table 7: ANOVA for repeated measures (SOCw)

Source	DF	Sum of squares	Mean squares	F	Pr > F	Adj. Pr>F G-G	Adj. Pr>F H-F
Repetition	2	0.209	0.105	0.676	0.510	0.505	0.510
Error	86	13.289	0.155				

(Own elaboration)

Table 8: Repetition / Tukey (HSD) with a confidence interval of 95% (SOCw)

Contrast	Difference	Standardized difference	Critical value	Pr > Diff	Significant
Repetition-II vs Repetition-I	0.096	0.152	2.371	0.987	No
Repetition-II vs Repetition-III	0.064	0.099	2.371	0.995	No
Repetition-III vs Repetition-I	0.032	0.050	2.371	0.999	No
Tukey's d critical value:			3.353		

(Own elaboration)

Appendix B: Time test for methodology modification

Table 9: Time test for total soil carbon

Vegetation	Soil type	Time (h)	TSC %	Date
Semi-evergreen low rainforest	Leptosol	0.5	64.60	12.05.17
Semi-evergreen low rainforest	Leptosol	1	67.51	15.05.17
Semi-evergreen low rainforest	Leptosol	2	66.93	15.05.17
Semi-evergreen low rainforest	Leptosol	4	67.82	16.05.17
Semi-evergreen low rainforest	Vertisol	0.5	30.54	12.05.17
Semi-evergreen low rainforest	Vertisol	1	34.65	15.05.17
Semi-evergreen low rainforest	Vertisol	2	34.38	15.05.17
Semi-evergreen low rainforest	Vertisol	4	35.22	16.05.17
Coastal dune	Arenosol	0.5	10.78	12.05.17
Coastal dune	Arenosol	1	44.78	15.05.17
Coastal dune	Arenosol	2	43.58	15.05.17
Coastal dune	Arenosol	4	45.06	16.05.17

The table above shows the time test done for three types of soil with high, medium and low organic matter. For the time test, only Arenosol reported a rare data during the first 30 minutes combustion. On the date, 7th of March 2017, the same sample recorded was 36.25%. Which means, there could be a lack of oxygen or other factors that cause incomplete combustion on 12th of May 2017. Hence, it is concluded that the time used during loss-on-ignition has minor differences in reporting the final TSC% (Own elaboration).

Appendix C: Carbon sequestration in each combination of vegetation and soil

Table 10: Percentage of soil carbon estimated from the vegetation and soil combination

#	Vegetation	Soil type	Soil Carbon (%)				pH	EC (dS m^{-1})	BD (g cm^{-3})	CR (%)	TH (cm)
			TSC	SOCw	SIC	N/Id					
1	CDV	Arenosol	36.41	0.26	6.66	29.49	8.18	0.32	1.15	0.00	30.00
2	CSI	Arenosol	41.95	3.33	5.70	32.92	7.91	0.70	0.82	0.00	30.00
3	FLF	Gleysol	34.55	6.45	5.04	23.07	7.44	0.61	1.01	0.00	30.00
4	FLF	Leptosol	36.58	7.44	2.94	26.20	7.39	0.74	0.76	10.00	12.00
5	FLF	Vertisol	16.76	2.86	0.48	13.42	6.03	0.47	1.03	20.00	30.00
6	Induced palm	Arenosol	37.19	1.33	7.59	28.28	7.69	1.25	0.81	0.00	30.00
7	Induced palm	Regosol	38.08	3.02	7.50	27.56	7.74	0.69	0.99	10.00	30.00
8	Mangrove	Gleysol	43.42	1.92	7.56	33.94	8.01	2.21	0.90	0.00	30.00
9	Mangrove	Histosol	44.32	9.36	5.28	29.68	7.54	14.18	0.30	0.00	30.00
10	Mangrove	Leptosol	54.87	9.10	1.32	44.45	6.74	7.54	0.34	0.00	8.00
11	Mangrove	Regosol	41.75	2.76	7.65	31.35	7.02	1.90	0.79	0.00	30.00
12	Mangrove	Solonchak	41.95	1.14	5.64	35.16	7.59	15.29	0.99	0.00	30.00
13	Natural palm	Arenosol	30.30	2.70	2.88	24.71	7.62	0.60	0.87	0.00	30.00

14	Marshland	Gleysol	21.23	1.98	5.84	13.41	7.62	0.67	1.00	0.00	30.00
15	SdLF	Cambisol	24.75	4.37	0.83	19.55	6.72	0.46	0.93	2.50	30.00
16	SdLF	Gleysol	27.39	3.22	0.42	23.74	6.76	0.42	0.90	0.00	30.00
17	SdLF	Leptosol	40.35	7.90	4.80	27.65	7.56	0.68	0.74	90.00	18.00
18	SdLF	Luvisol	26.15	2.24	0.24	23.67	6.59	0.37	0.79	0.00	30.00
19	SdLF	Nitisol	25.39	5.67	0.36	19.36	7.07	0.41	0.91	0.00	30.00
20	SdLF	Vertisol	25.18	2.34	2.10	20.74	7.62	0.33	1.14	0.00	30.00
21	SdMF	Kastanozem	27.66	4.32	0.54	22.81	6.92	0.42	0.85	20.00	30.00
22	SdMF	Leptosol	38.01	12.32	1.44	24.25	6.88	0.51	1.24	80.00	23.00
23	SdMF	Phaeozem	23.65	4.11	0.84	18.70	7.34	0.55	1.00	0.00	30.00
24	SeLF	Fluvisol	41.22	6.86	2.64	31.72	7.29	4.05	0.71	20.00	30.00
25	SeLF	Leptosol	53.72	8.92	1.74	43.06	7.26	0.66	0.68	2.50	14.50
26	SeLF	Luvisol	31.38	2.86	0.33	28.19	6.80	0.42	0.79	0.00	30.00
27	SeLF	Phaeozem	37.36	4.89	1.94	30.53	7.17	0.56	0.70	0.00	30.00
28	SeLF	Regosol	41.58	5.10	7.62	28.86	8.14	0.55	0.58	10.00	30.00
29	SeLF	Vertisol	34.08	4.37	3.09	26.62	7.36	0.60	0.77	12.50	30.00
30	SeMF	Cambisol	27.55	2.29	0.00	25.26	7.18	0.57	0.89	0.00	30.00
31	SeMF	Gleysol	28.13	3.33	1.08	23.72	6.82	0.50	0.86	0.00	30.00
32	SeMF	Leptosol	31.09	3.28	4.08	23.74	7.10	0.43	0.74	80.00	30.00
33	SeMF	Luvisol	30.24	2.50	0.00	27.74	6.92	0.16	0.74	0.00	30.00
34	SeMF	Phaeozem	33.71	6.45	0.42	26.85	7.34	0.47	0.86	0.00	30.00
35	SeMF	Vertisol	37.98	9.52	4.26	24.20	7.39	0.67	0.60	10.00	30.00
36	TLF	Gleysol	18.65	3.80	0.24	14.62	6.51	0.36	0.90	5.00	30.00
37	TLF	Phaeozem	47.76	8.94	2.04	36.77	7.56	2.00	0.68	20.00	30.00
38	Thule swamp	Histosol	45.98	8.74	7.50	29.74	7.17	2.61	0.30	0.00	30.00

The table shows the soil density and soil properties of the 38 different combinations. The TSC is the sum of SOCw, SIC and N/Id (unidentified content). (CDV = Coastal dune vegetation, CSI = Coastal Shrubland, FLF = Flooded low rainforest, SdLF = Semi-deciduous low rainforest, SdMF = Semi-deciduous medium rainforest, SeLF = Semi-evergreen low rainforest, SeMF = Semi-evergreen medium rainforest, and TLF = Thorny low rainforest) (Own elaboration).

Table 11: Soil carbon density estimated from the vegetation and soil combination

			Soil carbon density (Mg C ha^{-1})				
#	Vegetation	Soil type	TSC	SOCw	SIC	N/Id	Soil Texture
1	Coastal dune	Arenosol	1256.22	8.97	229.78	1017.48	Sand
2	Coastal shrubland	Arenosol	1030.64	81.77	140.05	808.82	Loamy sand
3	Flooded low rainforest	Gleysol	1046.97	195.37	152.72	698.88	Sandy loam
4	Flooded low rainforest	Leptosol	300.21	61.03	24.13	215.05	Loamy sand
5	Flooded low rainforest	Vertisol	414.19	70.70	11.87	331.63	Clay
6	Induced palm	Arenosol	898.20	32.02	183.30	682.88	Loamy sand
7	Induced palm	Regosol	1017.75	80.62	200.48	736.65	Sand
8	Mangrove	Gleysol	1172.35	51.95	204.12	916.28	Loamy sand

9	Mangrove	Histosol	398.88	84.24	47.52	267.12	Sandy loam
10	Mangrove	Leptosol	149.25	24.75	3.59	120.91	Loamy sand
11	Mangrove	Regosol	983.33	64.90	180.16	738.26	Loamy sand
12	Mangrove	Solonchak	1245.80	33.98	167.51	1044.31	Loamy sand
13	Natural palm	Arenosol	790.72	70.57	75.17	644.98	Loamy sand
14	Marshland vegetation	Gleysol	636.79	59.28	175.20	402.31	Silt loam
15	Semi-deciduous low rainforest	Cambisol	673.29	118.82	22.58	531.90	Sandy clay loam
16	Semi-deciduous low rainforest	Gleysol	739.48	87.05	11.34	641.09	Clay
17	Semi-deciduous low rainforest	Leptosol	53.75	10.53	6.39	36.83	Sandy clay loam
18	Semi-deciduous low rainforest	Luvisol	619.78	52.99	5.69	561.10	Sandy clay loam
19	Semi-deciduous low rainforest	Nitisol	693.16	154.74	9.83	528.59	Sandy clay loam
20	Semi-deciduous low rainforest	Vertisol	861.15	80.03	71.82	709.30	Clay
21	Semi-deciduous medium rainforest	Kastanozem	564.34	88.05	11.02	465.28	Sandy clay loam
22	Semi-deciduous medium rainforest	Leptosol	216.83	70.30	8.21	138.32	Sandy clay loam
23	Semi-deciduous medium rainforest	Phaeozem	709.42	123.24	25.20	560.98	Clay
24	Semi-evergreen low rainforest	Fluvisol	702.45	116.96	44.99	540.50	Silt loam
25	Semi-evergreen low rainforest	Leptosol	516.40	85.73	16.73	413.94	Sandy clay loam
26	Semi-evergreen low rainforest	Luvisol	738.96	67.35	7.77	663.83	Clay
27	Semi-evergreen low rainforest	Phaeozem	784.46	102.65	40.74	641.07	Sandy clay
28	Semi-evergreen low rainforest	Regosol	651.13	79.80	119.33	452.00	Sand
29	Semi-evergreen low rainforest	Vertisol	689.87	88.43	62.56	538.88	Sandy clay loam
30	Semi-evergreen medium rainforest	Cambisol	735.54	61.09	0.00	674.45	Clay
31	Semi-evergreen medium rainforest	Gleysol	725.65	85.86	27.86	611.93	Clay
32	Semi-evergreen medium rainforest	Leptosol	138.05	14.55	18.12	105.39	Sandy clay
33	Semi-evergreen medium rainforest	Luvisol	671.29	55.41	0.00	615.88	Silt loam
34	Semi-evergreen medium rainforest	Phaeozem	869.83	166.36	10.84	692.63	Clay loam
35	Semi-evergreen medium rainforest	Vertisol	615.21	154.16	69.01	392.03	Sandy loam
36	Thorny low rainforest	Gleysol	479.51	97.58	6.17	375.76	Clay
37	Thorny low rainforest	Phaeozem	779.37	145.97	33.29	600.11	Sandy loam
38	Thule swamp	Histosol	413.78	78.62	67.50	267.66	Sandy loam

The soil carbon density is estimated using the BD, CR, and TH (Own elaboration).

Table 12: Descriptive statistics of soil carbon density (Mg C ha^{-1})

Statistic / Var.	TSC	SOCw	SIC	N/Id
Min	53.75	8.97	0.00	36.83
Max	1256.22	195.37	229.78	1044.31
Q_1	528.39	59.72	10.88	394.60
Median	697.80	79.92	30.58	561.04
Q_3	843.54	95.30	108.29	680.77
Mean	683.79	81.75	65.59	536.45
S^2	85376.32	1823.89	5086.65	57446.07

S	292.19	42.71	71.32	239.68

(Own elaboration)

Appendix D: Soil carbon and properties per soil type

Table 13: Soil carbon and soil properties

#	Soil type	TSC (%)	SOCw (%)	SIC (%)	N/Id (%)	Sand (%)	Clay (%)	Silt (%)	pH	EC (dS m^{-1})	BD (g cm^{-3})	CR (%)	TH (cm)
1	Arenosol	36.58	1.53	6.18	28.86	89.03	9.54	1.48	7.88	0.74	0.93	0	30
2	Cambisol	25.68	3.67	0.55	21.46	45.41	34.92	19.67	6.87	0.50	0.92	2	30
3	Fluvisol	41.22	6.86	2.64	31.72	42.60	8.68	48.72	7.29	4.05	0.71	20	30
4	Gleysol	28.89	3.45	3.36	22.08	47.84	30.97	21.19	7.19	0.79	0.93	1	30
5	Histosol	45.15	9.05	6.39	29.71	53.24	3.04	43.72	7.36	8.40	0.30	0	30
6	Kastanozem	27.66	4.32	0.54	22.81	55.32	26.68	18.00	6.92	0.42	0.85	20	30
7	Leptosol	44.05	8.27	2.58	33.20	68.34	18.71	12.95	7.17	1.60	0.74	38	17
8	Luvisol	29.79	2.61	0.23	26.95	44.14	31.36	24.50	6.78	0.34	0.78	0	30
9	Nitisol	25.39	5.67	0.36	19.36	49.32	26.68	24.00	7.07	0.41	0.91	0	30
10	Phaeozem	35.62	6.10	1.31	28.21	46.78	34.54	18.68	7.35	0.89	0.81	5	30
11	Regosol	40.47	3.62	7.59	29.26	85.25	7.07	7.68	7.63	1.05	0.79	7	30
12	Solonchak	41.95	1.14	5.64	35.16	80.60	11.40	8.00	7.59	15.29	0.99	0	30
13	Vertisol	29.61	4.69	2.60	22.32	50.49	30.77	18.74	7.15	0.53	0.86	11	30

(Own elaboration)

Table 14: Descriptive statistics of soil carbon and soil properties

Statistic / Var.	TSC (%)	SOCw (%)	SIC (%)	N/Id (%)	Sand (%)	Clay (%)	Silt (%)	pH	EC (dS m^{-1})	BD (g cm^{-3})	CR (%)	TH (cm)
Min	16.76	0.00	0.00	13.41	25.32	1.32	0.00	6.03	0.16	0.30	0.00	8.00
Max	66.34	12.32	7.65	52.13	96.60	64.68	58.00	8.46	15.29	1.24	90.00	30.00
Q_1	27.63	2.65	0.53	23.71	44.60	8.43	7.80	6.91	0.43	0.73	0.00	30.00
Median	35.33	3.72	2.37	27.12	55.96	15.04	14.00	7.33	0.56	0.86	0.00	30.00
Q_3	41.13	6.45	5.66	29.84	80.92	35.90	22.50	7.57	0.71	0.92	10.00	30.00
Mean	34.91	4.64	3.20	27.07	60.05	22.66	17.30	7.27	1.58	0.82	9.32	27.95
S^2	90.09	8.80	7.62	52.42	433.30	307.74	198.04	0.23	10.03	0.04	455.34	31.58
S	9.49	2.97	2.76	7.24	20.82	17.54	14.07	0.48	3.17	0.21	21.34	5.62

(Own elaboration)

Appendix E: Principal component analysis of soil properties to soil carbon

Table 15: Correlation matrix of soil properties (Pearson)

Variables	TSC	SOCw	SIC	N/Id	Sand	Clay	Silt	pH	EC	BD	CR
TSC	**1**	0.37	**0.70**	**0.92**	0.48	**-0.81**	0.11	**0.62**	**0.59**	-0.54	0.30
SOCw	0.37	**1**	-0.11	0.10	-0.40	-0.16	**0.64**	-0.20	-0.06	**-0.75**	0.50
SIC	**0.70**	-0.11	**1**	0.55	**0.75**	**-0.82**	-0.22	**0.86**	0.48	-0.26	-0.18
N/Id	**0.92**	0.10	0.55	**1**	0.51	**-0.68**	-0.03	**0.56**	**0.63**	-0.29	0.29
Sand	0.48	-0.40	**0.75**	0.51	**1**	**-0.61**	**-0.71**	**0.78**	0.30	0.20	0.00
Clay	**-0.81**	-0.16	**-0.82**	**-0.68**	**-0.61**	**1**	-0.12	**-0.70**	-0.55	0.47	-0.07
Silt	0.11	**0.64**	-0.22	-0.03	**-0.71**	-0.12	**1**	-0.36	0.11	**-0.66**	0.06
pH	**0.62**	-0.20	**0.86**	**0.56**	**0.78**	**-0.70**	-0.36	**1**	0.38	0.01	-0.17
EC	**0.59**	-0.06	0.48	**0.63**	0.30	-0.55	0.11	0.38	**1**	-0.19	-0.18
BD	-0.54	**-0.75**	-0.26	-0.29	0.20	0.47	**-0.66**	0.01	-0.19	**1**	-0.12
CR	0.30	0.50	-0.18	0.29	0.00	-0.07	0.06	-0.17	-0.18	-0.12	**1**

Values in bold are different from 0 with a significance level alpha=0.05 (Own elaboration).

Table 16: Correlations between variables and factors (Principal Component Analysis)

	F1	**F2**	**F3**	**F4**	**F5**
TSC	0.907	0.349	0.145	0.090	-0.089
SOCw	0.038	**0.902**	**0.200**	-0.209	-0.109
SIC	**0.893**	-0.173	-0.179	-0.289	-0.005
N/Id	0.839	0.159	**0.206**	0.382	-0.074
Sand	**0.746**	-0.568	0.240	-0.142	-0.052
Clay	-0.906	-0.176	0.089	**0.146**	-0.255
Silt	-0.133	**0.863**	-0.378	0.049	**0.290**
pH	**0.834**	-0.345	-0.047	-0.237	0.119
EC	0.650	0.068	-0.374	0.596	-0.044
BD	-0.327	-0.826	**0.202**	0.265	**0.246**
CR	0.054	0.410	0.877	**0.110**	0.152

Values in bold are variables strongly bound with the factor (Own elaboration).

Appendix F: Soil carbon density and capacity in the State of Quintana Roo

Table 17: The range of soil carbon density estimated in the State of Quintana Roo

Soil type	**Soil carbon density (Mg C ha^{-1})**			
	TSC	**SOCw**	**SIC**	**N/Id**
AR	1023.93 ± 86.41	42.94 ± 12.92	173.01 ± 27.59	807.97 ± 72.41
CM	694.53 ± 35.53	99.37 ± 22.62	14.96 ± 11.53	580.20 ± 68.65
FL	702.45 ± 0.00	116.96 ± 0.00	44.99 ± 0.00	540.50 ± 0.00
GL	798.29 ± 106.17	95.30 ± 21.09	92.92 ± 37.00	610.07 ± 81.78

HS	406.33	±	7.45	81.43	±	2.81	57.51	±	9.99	267.39	±	0.27
KS	564.34	±	0.00	88.05	±	0.00	11.02	±	0.00	465.28	±	0.00
LP	347.25	±	66.59	65.18	±	11.74	20.34	±	2.77	261.73	±	55.91
LV	692.53	±	35.76	60.75	±	4.28	5.23	±	1.80	626.55	±	31.16
NT	693.16	±	0.00	154.74	±	0.00	9.83	±	0.00	528.59	±	0.00
PH	822.24	±	32.84	140.75	±	13.81	30.24	±	6.40	651.25	±	28.20
RG	889.53	±	116.89	79.63	±	5.11	166.83	±	24.38	643.07	±	95.15
SC	1245.80	±	0.00	33.98	±	0.00	167.51	±	0.00	1044.31	±	0.00
VR	681.94	±	72.23	108.01	±	14.95	59.97	±	15.17	513.95	±	65.60

The above data shows the soil carbon density and the standard error of each Soil type. (AR = Arenosol, CM = Cambisol, FL = Fluvisol, GL = Gleysol, HS = Histosol, KS = Kastanozem, LP = Leptosol, LV = Luvisol, NT = Nitisol, PH = Phaeozem, RG = Regosol, SC = Solonchak, and VR = Vertisol). The standard error with value “0” refers to soils that didn’t have any repetitions. In other words, there was no standard deviation in theses soils (Own elaboration).

Table 18: The range of soil carbon stock estimated in the State of Quintana Roo

Soil type	Freq.	Area (ha)	Soil carbon capacity (MtC)											
			TSC			SOCw			SIC			N/Id		
AR	622	52624	53.88	±	4.55	2.26	±	0.68	9.10	±	1.45	42.52	±	3.81
CM	616	255075	177.16	±	9.06	25.35	±	5.77	3.82	±	2.94	147.99	±	17.51
FL	5	267	0.19	±	0.00	0.03	±	0.00	0.01	±	0.00	0.14	±	0.00
GL	3386	782927	625.01	±	83.12	74.61	±	16.52	72.75	±	28.96	477.64	±	64.03
HS	17	63381	25.75	±	0.47	5.16	±	0.18	3.65	±	0.63	16.95	±	0.02
KS	75	7329	4.14	±	0.00	0.65	±	0.00	0.08	±	0.00	3.41	±	0.00
LP	7376	2452347	851.58	±	163.31	159.84	±	28.80	49.88	±	6.79	641.86	±	137.11
LV	813	278485	192.86	±	9.96	16.92	±	1.19	1.46	±	0.50	174.48	±	8.68
NT	184	45746	31.71	±	0.00	7.08	±	0.00	0.45	±	0.00	24.18	±	0.00
PH	1306	575976	473.59	±	18.91	81.07	±	7.95	17.42	±	3.69	375.11	±	16.24
RG	35	1701	1.51	±	0.20	0.14	±	0.01	0.28	±	0.04	1.09	±	0.16
SC	291	114348	142.45	±	0.00	3.89	±	0.00	19.15	±	0.00	119.41	±	0.00
VR	707	377515	257.44	±	27.27	40.78	±	5.64	22.64	±	5.73	194.03	±	24.76
TOTAL	**15433**	**5007720**	**2837.27**	**±**	**316.85**	**417.76**	**±**	**66.74**	**200.69**	**±**	**50.74**	**2218.82**	**±**	**272.32**

The above data shows the soil carbon capacity and the standard error of each Soil type. (AR = Arenosol, CM = Cambisol, FL = Fluvisol, GL = Gleysol, HS = Histosol, KS = Kastanozem, LP = Leptosol, LV = Luvisol, NT = Nitisol, PH = Phaeozem, RG = Regosol, SC = Solonchak, and VR = Vertisol). The standard error with value “0” refers to soils that didn’t have any repetitions. In other words, there was no standard deviation in theses soils. The frequency (freq.) refers to the number of polygons that each Soil Type appears on the soil map. The area refers to the total surface area occupied by each Soil type. The carbon capacity is the multiplication between soil carbon density, and the area dominated (Own elaboration).