EMILY ANE DIONIZIO DA SILVA

LAND USE CHANGE, SOIL PHYSICAL PROPERTIES AND CARBON STOCKS AT A SANDY SOIL DOMAIN OF A CERRADO AGRICULTURE FRONTIER

Thesis submitted to the Applied Meteorology Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

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(Adviser)

Let not the wise boast of their wisdom

or the strong boast of their strength

or the rich boast of their riches,

but let the one who boasts boast about this:

that they have the understanding to know me,

that I am the Lord, who exercises kindness,

justice and righteousness on earth,

for in these I delight”

Jeremiah 9:23-24

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BIOGRAPHY

EMILY ANE DIONIZIO DA SILVA, daughter of César Henrique da Silva and Gercilane Fonseca Dionizio da Silva, was born in Guaratinguetá, on August 09, 1989. In December of 2010, she graduated in Biology at the Teresa D'Ávila University Center (FATEA) in Lorena, SP.

In August of 2013, she initiated my studies at the Graduate Program in Applied Meteorology at the Federal University of Viçosa (UFV). She concluded the Master Degree in Applied Meteorology with the work entitled "Influence of climate variability, fire and phosphorus limitation on vegetation structure and dynamics of the Amazon–Cerrado border" in February of 2015.

In March of 2015, she initiated the Doctorate at the Graduate Program in Applied Meteorology at UFV.

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APPENDIX A

LIST OF SYMBOLS

ψ_e – Air Entry Matric Potential

ψ_m – Soil Water Matric Potential

f_{csa} – Coarse Sand fraction

f_{fsa} – Fine Sand

f_s – Silt

K_{sat} – saturated hydraulic conductivity

θ – Volumetric Water Content

θ_s – Saturated Volumetric Water Content

θ_{fc} – Soil Water Content in Field Capacity

θ_{paw} – Soil Plant Availability Water

θ_{wp} – Soil Water Content in Wilt Point

ρ_a – Soil Bulk Density

ρ_s – Soil Particle Density

ΦM – Macroporosity

Φm – Microporosity

Φtot – Total Porosity

LIST OF ACRONYMS

AGB – Aboveground Biomass

ArMe – Arenosa Média

b – empirical Campbell Parameter

BGB – Belowground Biomass

CDO – Cerrado formation

CS – Carbon Stock

C_s – Carbon Stock in soil for one soil layer

DS – Disturbed Sample

FOR – Forest Formations

FF- Forest Formations class in OBahia

GF- Grassland Formations class in OBahia

INEMA – Instituto do Meio Ambiente e Recursos Hídricos

IPCC – Intergovernmental Panel on Climate Change

IRR – Irrigated Agriculture

IRR_C – Irrigated Agriculture class in OBahia

LC – Land Cover

LU – Land Use

LULCC – Land Use and Land Cover Classes

MATOPIBA – Acronym for the states Maranhão, Tocantins, Piauí and Bahia

MeA – Médio argilosa

MeAr – Médio Arenosa

OBahia – Digital plataform of Land Use and Land Cover Classification maps for Westrn Bahia

PAST – Pasture

$PAST_C$ – Pasture class in OBahia

PTFs – Pedotransfer functions

RAG – Rainfed Agriculture

RAG_C – Rainfed Agriculture class in OBahia

SCS – Soil Carbon Stock

SCS_{30} – Soil organic carbon for 0-30 cm layer

SCS_{60} – Soil organic carbon for 0-60 cm layer

SCS_{100} – Soil organic carbon for 0-100 cm layer

SF- Savanna Formation class in OBahia

SiBCS – Brazilian soil classification system

SOC – Soil organic carbon

SOCC - Soil Organic Carbon Concentration

SWRC – Soil Water Retention Curve

TCS – Total Carbon Stock

UNFCCC – United Nations Framework Convention on Climate Change

US – Undisturbed Sample

USDA – Soil Classification System of United States Department of Agriculture

WBCM – Western Bahia Carbon Model

ABSTRACT

SILVA, Emily Ane Dionizio da, D.Sc.,Universidade Federal de Viçosa, March, 2019. **Land use change, soil physical properties and carbon stocks at a sandy soil domain of a Cerrado agriculture frontier**. Adviser: Marcos Heil Costa.

The rapid expansion of agriculture in the Brazilian Cerrado has raised concerns about water resources conservation and about greenhouse gases emissions. The largest and most dynamic agricultural frontier of the country known as MATOPIBA is located in this biome, also the largest producer of cotton, the Western Bahia. In order to evaluate how the land use changes affect the physical and hydraulic soil properties and carbon emissions in this region, this study collected data on physical soil properties and carbon stocks for different land use, land cover types, and developed an historical reconstruction of spatial patterns of carbon stocks during the 1990-2018 period. There are seven main conclusions in this thesis: First, intensive soil use increases soil compaction and reduces the saturated hydraulic conductivity (water infiltration velocity) of the soil. Analysis of physical and hydraulic properties indicate that soils under intensive use (Irrigated Agriculture, Rainfed Agriculture and Pasture) present higher density and lower saturated hydraulic conductivity than soils under natural vegetation (Forest Formations and native Cerrado). Second, intensive land use can increase the occurrence of surface runoff events. Although soils of Western Bahia present high infiltration capacity, its intensive use decreases this capacity and increases the chances of erosion. For rainfall with intensity of 50 mm hour^{-1}, surface runoff is expected in 62% of Irrigated areas, 41% of Pasture areas, 29% of Rainfed Agriculture areas, 15% of Forest areas and 5% of the Cerrado areas visited. For rainfall with intensity of 100 mm hour^{-1}, it is expected that surface runoff will occur in 95% of Irrigated areas, 73% of Pasture areas, 62% of Rainfed Agriculture areas, 20% of Forest areas and 32% of Cerrado areas visited. Absence of runoff should occur only in cases of rainfall intensity of less than 10 mm hour^{-1} or less. Third, it is extremely likely that the replacement of Forest Formations by Pasture implies in a reduction of SCS_{100} by 37.3% (p-value = 0.031), and it is very likely that the replacement of Forest Formations by Rainfed Agriculture reduces SCS_{100} by 30.3% (p-value = 0.053). Fourth, it is likely that conversion of savanna formations to Rainfed Agriculture or Pasture decreases SCS_{100} by 18.2%(p-value = 0.269) and 26.4% (p-value = 0155). Fifth, it is more likely than not that the conversion of Forest Formations to Irrigated Agriculture reduces SCS_{100}, and that conversion of Cerrado Formations to Irrigated Agriculture increases the SCS_{100} by 11.1% (p-value = 0.455). Sixth, it is extremely likely that the conversion of Pasture (p-value = 0.022) or Rainfed Agriculture (p-value = 0.034) to Irrigated Agriculture increases SCS_{100}. Finally, it was estimated that, historically, Western Bahia lost 7.74% of the total carbon stock, with a decrease from 112 Tg-C in 1990 to 103 Tg-C in 2018. Despite the limitations and uncertainties associated with our results, it is possible to conclude that the impacts of land use change are a reality on the agricultural frontier of the Cerrado and there is an urgent need to monitor how these changes occur over time. A temporal monitoring of these effects is crucial to identify management practices and the time scale needed to change the carbon loss trend, contributing to the development of effective gas emission mitigation strategies and the development of sustainable agriculture in the region.

RESUMO

SILVA, Emily Ane Dionizio da, D.Sc., Universidade Federal de Viçosa, março de 2019. **Mudança de uso de solo, propriedades físicas e estoque de carbono no solo em um domínio arenoso de uma fronteira agrícola do Cerrado**. Orientador: Marcos Heil Costa.

A rápida expansão da agricultura no Cerrado brasileiro tem trazido preocupações quanto à conservação dos recursos hídricos e às emissões de gases de efeito estufa. A maior e mais dinâmica fronteira agrícola do país, conhecida como MATOPIBA, está localizada neste bioma, e também é a maior região produtora de algodão do país, o Oeste da Bahia. Com o objetivo de avaliar como a mudança de uso do solo nesta região afeta as propriedades físicas e hidráulicas do solo da região, e o balanço de carbono, este estudo coletou dados de propriedades físicas e hidráulicas, e de estoque de carbono do solo para diferentes tipos de uso e cobertura da terra, seguido pela elaboração de uma reconstrução histórica dos padrões espaciais de carbono no período de 1990 a 2018. Esta tese chegou a sete conclusões principais: Primeiro, o uso intensivo aumenta a compactação do solo e reduz a condutividade hidráulica saturada (velocidade de infiltração da água) do solo. As análises das propriedades físicas e hidráulicas indicam que solos sob uso intensivo (Agricultura Irrigada, Agricultura de Sequeiro e Pastagem) apresentam maior densidade e menor condutividade hidráulica saturada do que os solos sob vegetação natural (Formações Florestais e Cerrado nativo). Segundo, o uso intensivo do solo pode aumentar a ocorrência de eventos de escoamento superficial. Embora os solos do Oeste da Bahia apresentem alta capacidade de infiltração, o uso intensivo do solo diminui esta capacidade e aumenta as chances de erosão. Para chuvas de intensidade 50 mm h^{-1}, espera-se a ocorrência de escoamento superficial em 62% das áreas Irrigadas, 41% das áreas de Pastagem, 29% das áreas de Agricultura de Sequeiro, 15% das áreas de Floresta e 5% das áreas de Cerrado. Para chuvas de intensidade 100 mm $hora^{-1}$, espera-se que ocorra escoamento superficial em 95% das áreas Irrigadas, 73% das áreas de Pastagem, 62% das áreas de Agricultura de Sequeiro, 20% das áreas de Floresta e 32% das áreas de Cerrado. Ausência de escoamento superficial deve ocorrer apenas em chuvas de intensidade inferiores a 10 mm $hora^{-1}$. Terceiro, é extremamente provável que a substituição de Formações Florestais por Pastagem reduza os estoques de carbono no solo em 37.3% (p-valor = 0.031), e é muito provável que a substituição de Formações Florestais por Agricultura de Sequeiro reduza os estoques de carbono no solo em 30.3%

(p-valor = 0.053), para camada de 0-100 cm. Quarto, é provável que a conversão de Cerrado para Agricultura de Sequeiro ou Pastagem diminua o carbono no solo em 18.2% (p-valor = 0.269), e 26.4% (p-valor = 0.155), para camada de 0-100 cm. Quinto, existe mais de 50% de chance de que a conversão de Florestas em Agricultura Irrigada não reduza o estoque de carbono no solo (p-valor = 0.704), e que a conversão de Cerrado em Agricultura Irrigada aumente os estoques de carbono em 11.1% (p-valor = 0.455). Sexto, é extremamente provável que a conversão de Pastagens (p-valor = 0.022) ou de Agricultura de Sequeiro (p-valor = 0.034) em Agricultura Irrigada, aumente o estoque de carbono no solo de 0-100 cm. Por fim, estimou-se que historicamente o Oeste da Bahia perdeu 7.74% do total de carbono estocado com diminuição de 112 Tg-C em 1990 para 103 Tg-C em 2018. Apesar das limitações e incertezas associadas aos resultados, é possível concluir que os impactos da mudança de uso do solo são uma realidade na fronteira agrícola do Cerrado e que existe uma necessidade urgente de monitorar como essas mudanças ocorrem ao longo do tempo. O monitoramento temporal destes efeitos é crucial para identificar as práticas de manejo e o tempo necessário para mudar a tendência de perda de carbono, contribuindo para elaboração de estratégias efetivas de mitigação de emissões e desenvolvimento de uma agricultura sustentável na região.

GENERAL INTRODUCTION

Climate change is a scientific fact (Manabe and Wetherald 1967; Keeling et al., 1976; Hansen et al., 1981; Vitousek, 1994; Hansen et al., 2012; IPCC, 2013; Chalinnor et al., 2014). The most recent IPCC assessment has shown that global warming is likely to reach 1.5°C above pre-industrial levels between 2030 and 2052 if it continues to increase at the current rate (IPCC, 2013). The main direct and indirect impacts of global warming are related to risks from increase of droughts and precipitation deficits, global mean sea level rise, species loss and extinction, decrease of economic growth and risks to food security and water supply.

To avoid that Earth temperature exceeds 1.5°C above pre-industrial levels by the end of the century, 195 countries, including Brazil, have signed the Paris Agreement in which the signatory parties committed themselves to regulate and reduce greenhouse gas emissions. In this agreement, Brazil committed to reduce greenhouse gas emissions by 37% from 2005 levels until 2025, in addition to invest in biofuels, renewable energy sources, recover degraded Pastures and end illegal deforestation in the Amazon.

According to the IPCC SR1.5 report (IPCC, 2018), the Paris targets for warming limited to 1.5°C will only be achieved through CDR (Carbon Dioxide Removal) practices. These practices, to some extent, neutralize emissions from sources, for which no mitigation measures have been identified, and seeks to achieve net negative emissions. For tropical countries where agriculture activities are a major source of greenhouse gas emissions to atmosphere, the soil management of agricultural areas is one of the most important CDR practices.

The correct management of soils reduces carbon emissions, increases the soil carbon stocks (Maia et al., 2010; Fujisaki et al., 2015; Mahowald et al., 2017) and contributes to maintain both physic and hydraulic soil properties (Almeida et al., 2008;

Faria et al., 2010; Horel et al., 2015; Filizola et al., 2017; Anache et al., 2018). However, in some cases, mechanic procedures for native vegetation clearing, soil acidity, and fertility correction and crop planting can alter the soil structure, causing soil surface compaction, decreasing the soil total porosity and water retention capacity (Araújo et al. 2004; Figueiredo et al., 2008; Horel et al., 2015). In addition, when the soil surface is compacted, there is a reduction in the saturated hydraulic conductivity, resulting in potential changes to surface runoff, deep drainage and potential of soil carbon accumulation (Araújo et al., 2004; Fontana et al., 2011).

Thus, the knowledge about the influence of native vegetation replacement by agriculture on both physic and hydraulic soil properties and in the carbon stocks is fundamental to choose the best soil management options for soil carbon storage and soil water conservation.

In Brazil, currently the most important agricultural frontier is known as MATOPIBA (acronym for the states Maranhão, Tocantins, Piauí and Bahia) in Cerrado. The influence of land use change on soil physical properties and the water and carbon cycles of this region has been studied in the last decade (Almeida et al., 2008; Faria et al., 2010; Fontana et al., 2016; Spera et al., 2016; Filizola et al., 2017). However, most of these studies use a reduced number of data points, not allowing spatial generalizations. Remote sensing and modeling techniques in this scenario have been considered an alternative to evaluate the influence of land use change on the water balance (Dias et al., 2015; Spera et al., 2016; Przézdziecki et al., 2017; Moreira et al., 2018), in vegetation dynamics (Sano et al., 2011; Oliveira et al., 2017) and in climate (Wang et al., 2009; Malhado et al., 2010; Coe et al., 2013; Pires and Costa 2013) at the large scales. These studies generally combine both field data (parameters of soil or vegetation) and land surface models forced by climate data to determine how the suppression of native vegetation alters the amount of water and carbon recycled to the atmosphere (Spera et al., 2016), or affects the regional climate dynamics (Wang et al., 2009; Malhado et al., 2010; Coe et al., 2013; Pires and Costa 2013). These simulation results, however, are very sensitive to the soil physic and hydraulic parameters within the model (Dias et al., 2015), emphasizing the need to obtain representative field data in order to reduce the uncertainty of the simulations.

Thus, the knowledge of physic and hydraulic soil properties under both native vegetation and agriculture areas may contribute to the development of powerful modeling tools, such as hydrologic and dynamic vegetation models. In addition, they are fundamental to make inferences about soil quality and sustainability, supporting the development of alternatives that can prioritize water and soil conservation as well as the preservation of the remaining native vegetation, while ensuring an increase of agricultural production.

In this context, this thesis provides substantial new data to improve existing databases and regional modelling studies, while spatially evaluating of different scenarios of land use change. In Chapter 1, I present a soil physical database for three land use and two land cover classes – LULCCs (Rainfed and Irrigated agricultural lands, Pasture, Cerrado and Forest formations) and evaluate how these LULCCs influence the hydraulic and physical soil properties at the sandy soil domain of a Cerrado agricultural frontier. In addition, I develop pedotransfer functions to derive hydraulic properties for use in dynamic vegetation models. In Chapter 2, I provide a soil organic carbon database for these five LULCCs and evaluate how the land use change regionally affects the soil carbon stocks at the sandy soil domain of a Cerrado agricultural frontier, including a carbon balance historical reconstruction for the 1990-2018 period.

CHAPTER 1 - INFLUENCE OF LAND USE AND LAND COVER ON HYDRAULIC AND PHYSICAL SOIL PROPERTIES AT THE CERRADO AGRICULTURAL FRONTIER

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1.1 Introduction

In the last decade, the rapid expansion of agribusiness in the Cerrado led to a new Brazilian agricultural frontier known as MATOPIBA (acronym for the states Maranhão, Tocantins, Piauí and Bahia), which have raised concerns about the natural resources conservation (Oliveira et al., 2017; Nunes et al., 2017), especially regarding to the water availability (Brannstrom et al., 2008; Batistella et al., 2009; Spera et al., 2016).

In MATOPIBA, the Western Bahia stands out by the agricultural expansion, representing 49% of the total agricultural area (Carneiro-Filho et al., 2016), with 1.8 million hectares in 2015, which is equivalent to an increase of 352% since 1985 (Sano et al., 2011; AIBA et al., 2015). The irrigated croplands alone had an increase of 526% between 1985 and 2002, with a simultaneous decrease of Cerrado, seasonal forest and transition vegetation areas by 881,483 ha, 66,417 ha and 269,592 ha, respectively (Batistella et al., 2003). In fact, the region also stands out for its high productivity records, reaching 7.4 million tons of soybean, cotton and maize crops in the 2016/2017 harvest (AIBA, 2017).

The Western Bahia is located on the Urucuia Aquifer, a region with high water availability and natural resources drained by the Grande, Corrente and Carinhanha basins. This abundance of natural resources brings a major concern about the regional water availability and the impacts of the agricultural activities on Cerrado biome (Spera et al., 2016; Oliveira et al., 2017; Nunes et al., 2017). In this region, the soils are particularly considered "fragile" due the predominance of sandy soils from the Urucuia sandstone and quartz and characterized by low water retention capacity, low organic matter concentration and stability of aggregates (Fontana et al., 2017).

The effects of land use change on soil physical properties are broadly known, especially when considered conversion of tropical forest to Pasture or croplands (Elsembeer et al., 1999; Muller et al., 2011; Scheffler et al., 2011). Changes in soil bulk density, penetration resistance, porosity, near-surface hydraulic conductivity (Lal, 1996; Moraes et al., 1996; Zimmermann et al., 2006), infiltration and saturated hydraulic conductivity (Scheffler et al., 2011; Horel et al., 2015) are described as possible consequences of the land use change.

In Cerrado, these effects have been studied in the last decade (Almeida et al., 2008; Faria et al., 2010; Filizola et al., 2017), and received a greater focus due to the advancement of the agricultural frontier from Southern Amazonia to MATOPIBA (Spera et al., 2016; Filizola et al., 2017). The soil compaction (Nobrega et al., 2017; Bonetti et al., 2018), erosion (Anache et al., 2018), and decrease of permeability and water infiltration rates (Hunke et al., 2015; Nobrega et al., 2017) are some effects of land use change on the physical and hydraulic soil properties, causing damage on soil aeration and affecting soil water dynamics in Cerrado. However, most part of these studies is based on clayey soils and has a few data points and do not allow spatial generalizations. Remote sensing and modeling techniques have been used to broadly study the influence of land use on the water balance (Dias et al., 2015; Spera et al., 2016; Przézdziecki et al., 2017; Moreira et al., 2018), in the dynamic of vegetation (Sano et al., 2011; Oliveira et al., 2017) and climate (Wang et al., 2009; Malhado et al., 2010; Coe et al., 2013; Pires et al., 2013), and showed that the replacement of native vegetation by croplands in Cerrado alters the amount of water recycled to the atmosphere at the large-scale (Spera et al., 2016), affecting the regional climate dynamics (Wang et al., 2009; Malhado et al., 2010; Coe et al., 2013; Pires et al., 2013). The results of these simulations, however, are very sensitive to the soil physical and hydraulic parameterizations in the model.

Thus, the knowledge of the hydraulic and physical soil properties contribute to development of powerful tools as hydrological and dynamic vegetation models, and remote sensing techniques to estimates the water recharge, the soil water availability, the cropland productivity, or the influence of extreme precipitation scenarios in the sandy soil domain of Cerrado agriculture frontier. Moreover, the hydraulic and physical soil properties are fundamental to make inferences about the soil quality and sustainability allowing the development of alternatives that can prioritize the water and soil conservancy and preserve the remaining native vegetation while ensuring the increase of agricultural production.

The main goal of this study is to evaluate how land use and land cover affect the hydraulic and physical soil properties at a sandy soil domain of a Cerrado agriculture frontier – Western Bahia. In addition, pedotransfer functions were developed in order to derive hydraulic properties for sandy soils and use in dynamic vegetation models.

1.2 Methods

1.2.1 Study area

The study area of this work is the Western Bahia located on the geological formation of the Urucuia Group (*Upper Cretaceous*) which is one of the main areas of agricultural expansion in the Cerrado biome. This region is drained by three important rivers (Grande, Corrente and Carinhanha rivers), with an area of 131,168 km^2. Marked by the arrival of migrant rural producers from the Southern region in 1990, Western Bahia is today one of the largest producers of soybean in MATOPIBA and the largest producer of cotton in Brazil.

In this region, the soils are predominant sandy and have medium texture, classified as Latossolos (57%), Neossolos (29.6%) and Cambissolos (7%), according to the Brazilian soil classification system (Figure 1.1), and are characterized as deep soils, well drained, acidic (with high aluminum and Fe-oxides) with low fertility. The landscape is characterized as flat or mildly hilly areas, which allows the use of high level technology and the chemical inputs by correction of fertility providing favorable conditions to expansion and intensification of agriculture. The physiognomy vegetation is predominantly Cerrado *sensu stricto* with predominance of the tree-shrub stratum (IBGE, 1992).

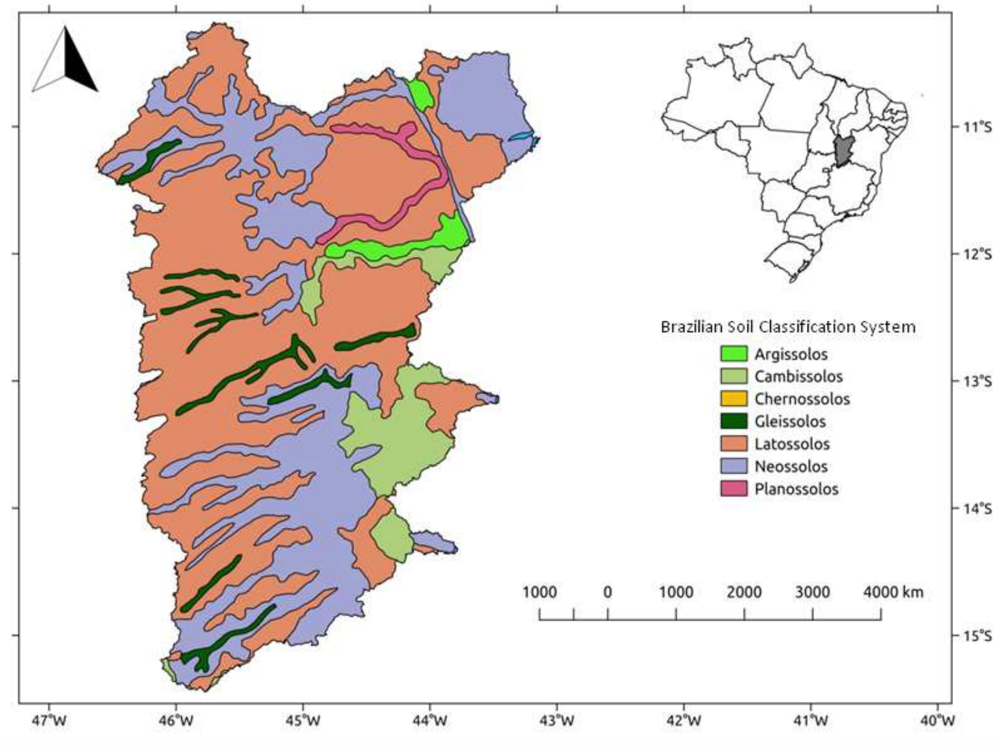


Figure 1.1. Soil classes in Western Bahia according to Brazilian Soil Classification (EMBRAPA, 2011).

The regional climate is tropical humid according to Köppen (IBGE, 1992), and present two well defined seasons, dry (May to September) and rainy (October to April). The average annual rainfall is 1,400 mm in the extreme west, gradually decreasing to 800 mm in the east (Figure 1.2). The altitude ranges between 1083 m in the extreme west, where there is the known as "chapadões" of Brazilian Cerrado, gradually decreasing to between 880 m and 680 m in the Central Western. In the northeastof the region, the altitude varies from 580 m to 380 m.

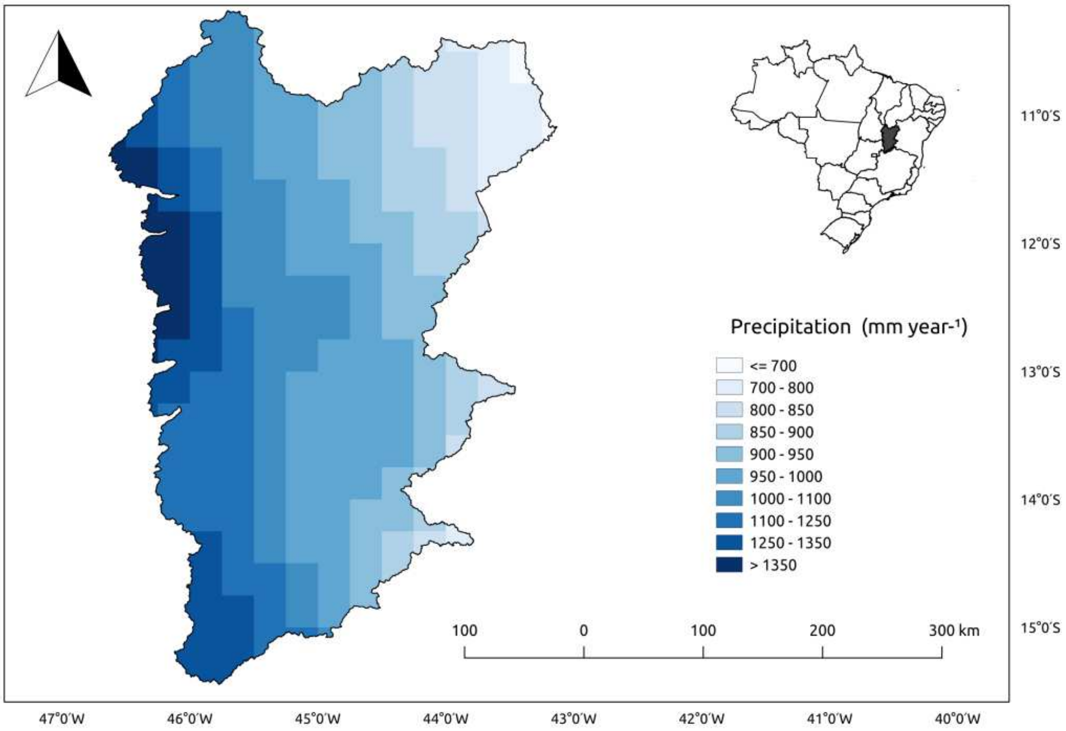


Figure 1.2. Average of precipitation for Western Bahia considering 1980-2015 period, according to Xavier et al. (2016) database (25 km of spatial resolution).

1.2.2 Soil sampling design

The soil samples were collected in two field campaigns in 2017 in Western Bahia for five land use and land cover classes (LULCCs): (1) Cerrado formations (CDO), (2) Forest formations (FOR), (3) Rainfed Agriculture (RAG), (4) Irrigated Agriculture (IRR), and (5) Pasture (PAST) (Figure 1.3). The RAG and IRR areas were covered for different croplands as maize, bean, soybean, corn, and was sampled in different stages of crop cycle. The IRR samples were collected in the middle of the crop cycle during July 2017, while samples of RAG were collected during November and December of 2017, at the beginning of the rainfed crop cycle. The CDO, FOR and PAST were also collected during November and December of 2017. The PAST soil samples were collected in well-managed pastures (areas under pasture rotation, without overgrazing and with establishment of confinement areas) and in pastures without management, with presence of termite mounds, soil compaction, low grass cover (Figure 1.4).

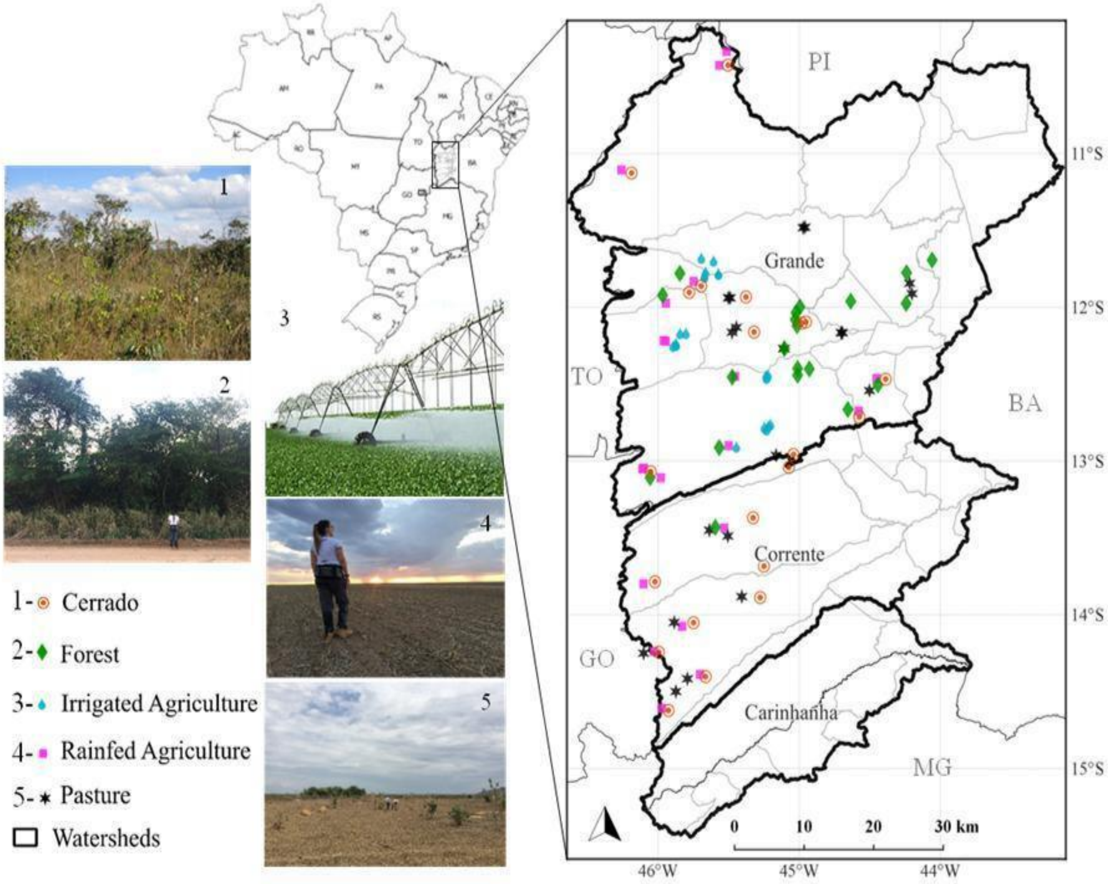


Figure 1.3. Study area and location of the soil samples collected considering different land use and land cover in Western Bahia.

Each LULCC was sampled at 20 sampling points following the criteria: opening year of the agriculture or Pasture area between 1990 and 2017, and logistic access to farms, including road conditions and permission to enter the farm by the farmer. In some cases, CDO and the FOR areas were sampled along the road between farms in natural vegetation areas rather than inside the farms. In total, 700 samples were collected considering 5 LULCCs × 20 sample points × 7 depth levels. At each sampling point, undisturbed samples were collected for 0-5, 5-10, 10-15, 15-20, 30, 50 and 70 cm of depth using an Uhland soil sampler, with metal cylinders of 100 cm^3 volume. The soil samples of 0-5 cm of depth were used to calculate the saturated hydraulic conductivity (K_{sat}), soil water content in field capacity and wilting point (θ_{fc}, θ_{wp}), texture (Coarse Sand - f_{csa}, Fine Sand - f_{fsa}, and Silt - f_s fractions), total porosity (Φ_{tot}), microporosity (Φ_m), macroporosity (Φ_M), soil particle density (ρ_s), while all layers (0-5, 5-10, 10-15, 15-20, 30, 50 and 70 cm) were used to calculate the soil bulk density (ρ_a).

Figure 1.4. Well managed pasture (b and c) and not managed pastures (a, d, and e) areas visited in Western Bahia to soil sample collection.

1.2.3. Measuring methods

The K_{sat} of soils was determined via the constant head permeameter method (Youngs, 1991). The constant water flow that flowed through the soil sample was measured and applied into the equation for direct calculation of K_{sat}. For textural analysis and particle density, samples were dried in the open air, and sieved in a 100 mash sieve. Soil fractions (f_{csa}, f_{fsa}, and f_s) were separated according to Ruiz (2005), using the sieve method for the sand fraction (2 - 0.05 mm) and the pipette method to determine the silt (0.05 - 0.002 mm) and clay (< 0.002 mm) fraction. The soil water retention curve (SWRC) was measured using a sand tension table at the matric potentials of -3 and -6 kPa, and a Richards chamber with porous plates, at matric potentials of -10, -50, -100, -500 and -1500 kPa (Richards, 1943). The centrifuge method was used to measure the soil water content at matric potential of -30 kPa. The SWRC was measured for 0 - 5 cm layer for all LULCCs, and for 5 – 20 cm layer in IRR areas. The ρ_a and Φ_{tot} analyses were carried out using methods described by EMBRAPA (1997). The microporosity (Φ_m) was determined by water content in a volumetric ring under a tension of 0.6 m of water column tension, and the soil macroporosity (Φ_M) was estimated by the difference between total soil porosity and soil microporosity.

1.2.4 Pedotransfer model

1.2.4.1. Adjustment of Soil Water retention curve

The Campbell and Norman (1998) soil model was fitted to soil water content data using Equation 1.1:

$$\Psi_m = \Psi_e \times \left(\frac{\theta}{\theta_s}\right)^{-b} \qquad (1.1)$$

where, Ψ_m is the soil water matric potential in kPa, Ψ_e is the air entry matric potential in kPa, θ is the volumetric water content cm^3 cm^{-3}, θ_s is the saturated volumetric water content cm^3 cm^{-3}, and b is the empirical Campbell parameter, related to the particle size distribution. b Campbell is strongly dependent on soil texture (Clapp et al., 1978) and is considered an index for soil pore-size distribution (Moldrup et al., 2001). This model was chosen due to its minimal set of parameters necessary to describe the soil hydraulic properties, favoring its implementation in regional and global scales, and it has been widely used in modeling studies (Van Looy et al., 2017; Chrysodonta et al., 2018).

A linear regression with log-transformed data was used into the equation $log_y = a + xb$, to determine the Ψ_e and the empirical value of b Campbell parameter, where a is the intercept of the soil water retention in the log-log system and b represents the slope.

The linear least squares method was used to adjust the Ψ_e and b Campbell constant for each sample. Then, the raw data were also used to develop the pedotransfer functions.

1.2.4.1 Development of Pedotransfer functions

The Pedotransfer functions (PTFs) were developed using the soil physic proprieties and the SWRC for 100 undisturbed samples collected in the 0-5 cm soil layer. Initially, I tested the normal distribution for fc_{sa}, f_{fsa}, fs, Φ_{tot}, Φ_M, Φ_m, ρ_s and ρ_a properties using Shapiro-Wilk statistic test considering $\alpha = 0.05$. The properties that are normally distributed were used to develop the PTF through multiple regression, while the predictors not normally-distributed, such as ρ_a, f_{fsa}, f_s, Φ_M and Φ_m, were excluded from the analysis.

To develop and validate the pedotransfer function, the observed data for water retention curve and physical properties were separated into two groups, in which the first one contains 75% of the data (Calibration Group) and the second 25% of the data

(Validation Group). The samples of Calibration and Validation Groups were randomly chosen. Between these two groups the average of soil physical properties were not significantly different at $\alpha = 0.05$ according to the Student *t* test, except for f_{csa} in the Forest formations areas. However, for hydraulic proprieties (Ψ_e and b), a significant difference was found between b Campbell parameter used in Calibration and Validation Group for CDO and FOR classes.

A multiple linear regression model was adjusted for each hydraulic Campbell parameters ($\log\Psi_e$, b, K_{sat}, θ_{fc}, θ_{wp}) using the soil physical properties measurements as predictors in Equation 1.2:

$$y = \beta_0 + \beta_1 \times \rho_a + \beta_2 \times \Phi_{tot} + \beta_3 \times f_{csa} \tag{1.2}$$

where, y is one of the five hydraulic parameters ($\log\Psi_e$, b, K_{sat}, θ_{fc}, θ_{wp}), ρ_a is the soil bulk density in g cm^{-3}, Φ_{tot} is the total soil porosity in cm^3 cm^{-3}, and f_{csa} represents the coarse sand fraction in %. The stepwise method with 5% of significance was chosen to select the most important variables for determination of y through the backward and forward mechanism. This stepwise method uses the Akaike criterion to eliminate collinear variables, excluding non-informative variables of the final model.

1.2.5. Data analysis

Homoscedastic and normality of residuals were tested applying the Shapiro-Wilk test (Wilk et al., 1965) for all soil physical properties, and used the Tukey-Cramer method to compare the soil physical properties among LULCCs.

The soil physical properties that were normally distributed (i.e., f_{csa}, Φ_{tot}, and ρ_a, that showed p-values greater than 0.05 in the Shapiro-Wilk test) were applied to the analysis of variance and were used for the development of Pedotransfer function. The t-test was used to compare the average of the 75% of soil properties used for the development and 25% used for the validation of pedotransfer function (0-5 cm layer), and for the comparisons of the differences for each soil layers among LULCCs. The validations of PTFs were evaluated using the Pearson correlation coefficient.

The all Ksat values for each LULCCs were used to calculate the probability of runoff occurrence, using 50 mm hour^{-1} and 100 mm hour^{-1} precipitation as reference value. All data analyses were carried out using R software.

1.3. Results

1.3.1. Soil physical and hydraulic properties

Most of the soil samples were sandy clay loams (40%), followed by 23.3% of sandy loams and 23.3% of loamy sands. The 13.4% of remaining samples were distributed among sandy clay, sand and silt clay classes (Figure 1.5).

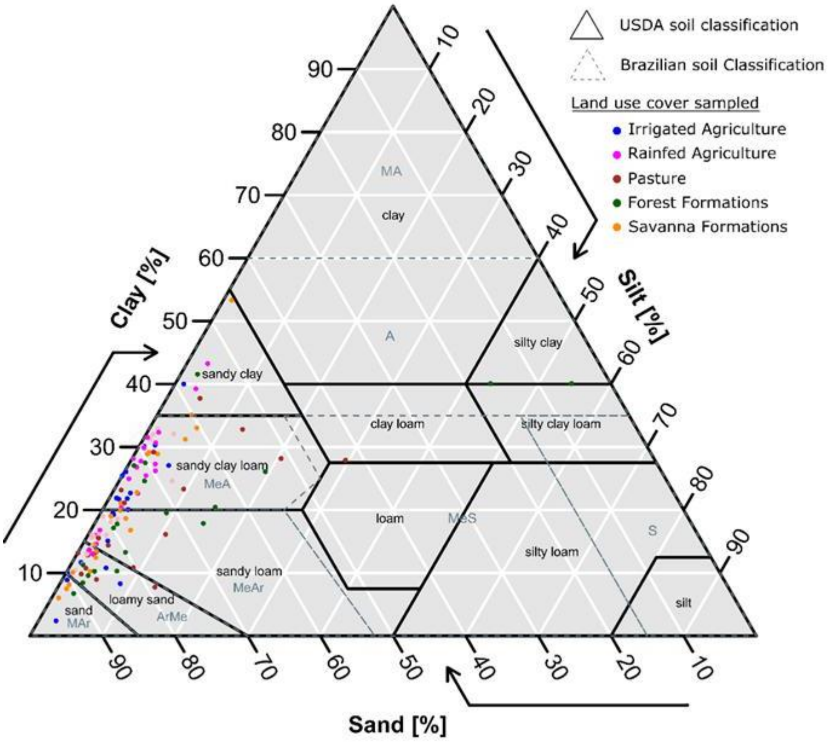


Figure 1.5. Average of soil texture fractions for 0-5 cm layer in Western Bahia according the USDA soil classification and to the Brazilian soil classification system – SiBCS.

In the Brazilian soil classification system (SiBCS), these samples presented a similar distribution along the soil classes, with predominance of 40% of the samples in MeA (Médio argilosa), and 56% divided equally between MeAr (Médio Arenosa) and ArMe (Arenosa Média) classes, highlighting the predominance of sandy soils in the region (Figure 1.5). The average sand content ranged between 69.47% and 85.79% within the predominant soil classes, while the average clay content ranged between 11.29% and 26.87%. The soils presents a coarse sand (f_{cs}) as a predominant fraction in the texture, followed by Fine sand (f_{fs}) and Silt (Figure 1.6a-c).

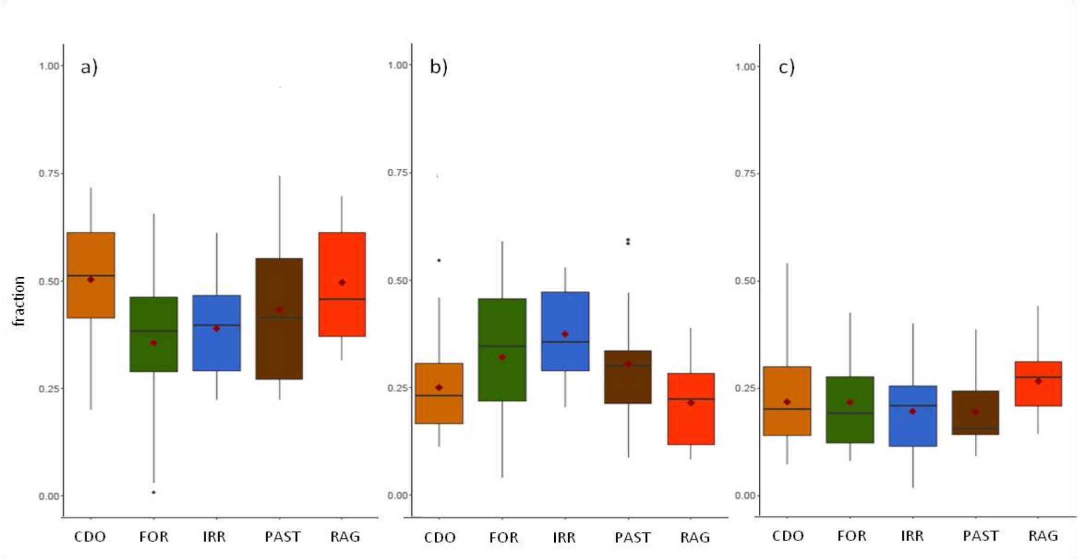


Figure 1.6. Fractions of a) Coarse sand; b) Fine sand and c) Clay considering 0-5 cm depth for different LULCCs in Western Bahia. In the box plots, the lower limit of the box indicates the 25th percentile, the black line within the box marks the median, the red point within the box marks the mean, and the upper limit of the box indicates the 75th percentile. Bars above and below the box indicate the confidence interval. The samples are distributed in: CDO = 22; FOR = 19; IRR = 20; PAST = 21; RAG = 20.

The results of average soil bulk density (ρ_a) suggest a compacted soil surface for agriculture land use, ranging between 1.52 ± 0.148 and 1.61 ± 0.138 g cm 3 (Figure 1.7a and Table 1.1). Under natural land cover, FOR and CDO, the ρ_a was lower and statistically different from agricultural areas with average ρ_a 1.36 ± 0.157 g cm^{-3} (Figure 1.7a and Table 1.1). Along the soil profile, the soil ρ_a showed an increase trend from 0-5 cm to 30 cm for all LULCCs (Figure 1.8). This increase of ρ_a in the subsurface layers is higher in areas under managed soil than in FOR and CDO soils, with values above 1.65 g cm^{-3} (Figure 1.8). The particles density (ρ_s) ranged between 2.52 ± 0.108 g cm^{-3} and 2.61 ± 0.070 g cm^{-3} for all LULCCs showing no statistical differences according to the Tukey-Cramer test.

The soil total porosity (Φ_{tot}) ranged between 26% and 60%, with average of 43% for all samples collected (Table 1.1, Figure 1.7b). The compaction pattern found in ρ_a is also observed in Φ_{tot}, with reduction of the Φ_M in agriculture land use compared to CDO and FOR areas. In natural ecosystems, Φ_{tot} ranged between 26% and 57% for CDO and between 38% and 60% for FOR, while in agriculture systems the Φ_{tot} ranged between 30% and 53% (Figure 1.7e). Average CDO and FOR Φ_{tot} is greater than 45%, while under agriculture land use Φ_{tot} were smaller than 41% (Table 1.1).

The soil compaction decreases Φ_M in PAST and RAG areas, reducing the soil capacity to drain excess water after a heavy precipitation - lower K_{sat} values. The reduction of Φ_M contributes to an increase of Φ_m which may alter the soil aeration and roots growing conditions. The Φ_M in managed areas ranged between 9% and 12%, while Φ_m were above 25%. Although the values of Φ_M and Φ_m of the IRR class were not measured, significant differences were found for total soil porosity in relation to CDO and FOR (Figure 1.7e).

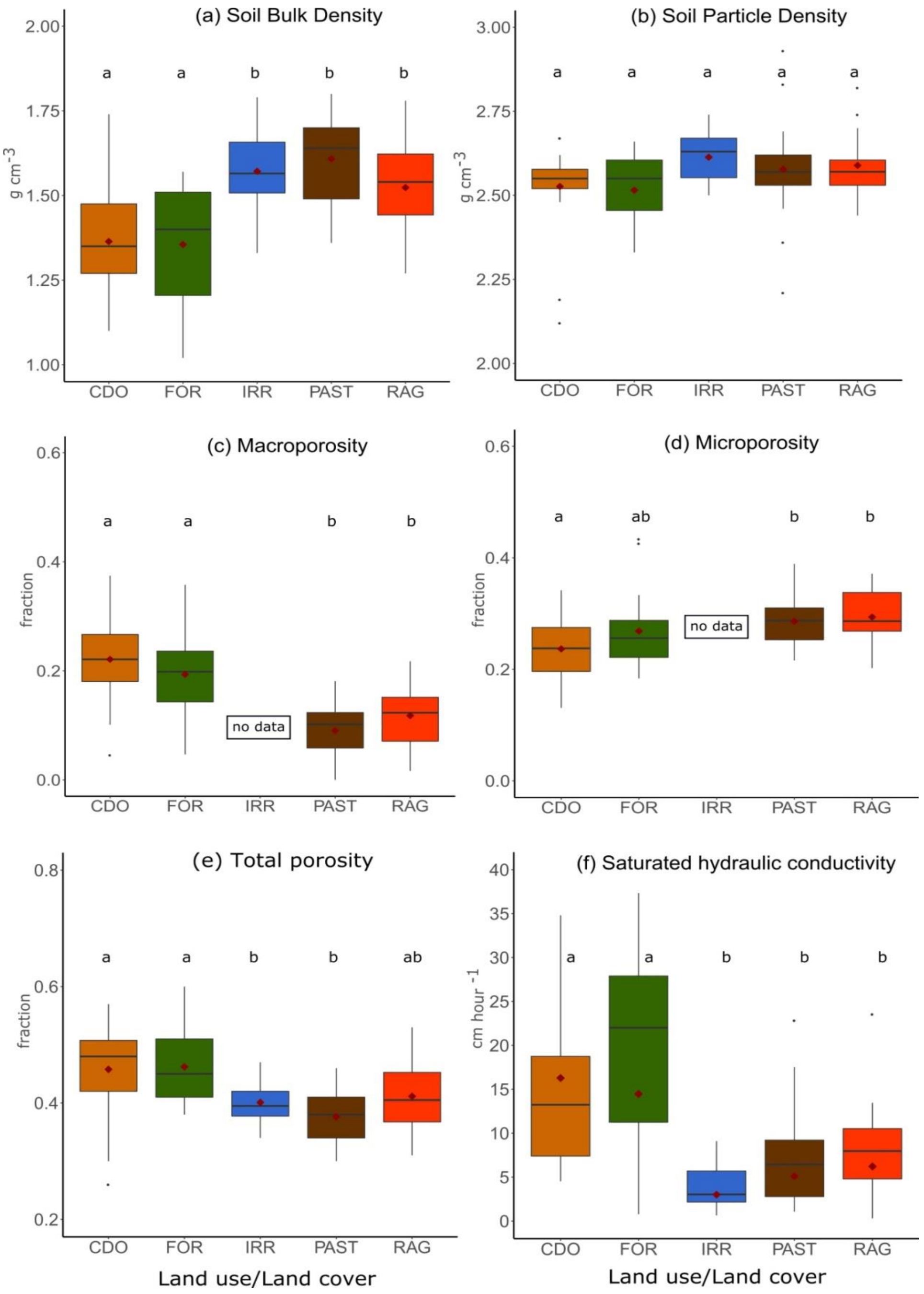


Figure 1.7. Soil hydraulic and physical properties considering 0 5 cm depth for different LULCCs in Western Bahia. . In the box plots, the lower limit of the box indicates the 25th percentile, the black line within the box marks the median, the red point within the box marks the mean, and the upper limit of the box indicates the 75th percentile. Bars above and below the box indicate the confidence interval. The samples are distributed in: CDO = 22; FOR = 19; IRR = 20; PAST = 21; RAG = 20. Different letters means that averages are statistically different according to Tukey Cramer test at α = 0.05.

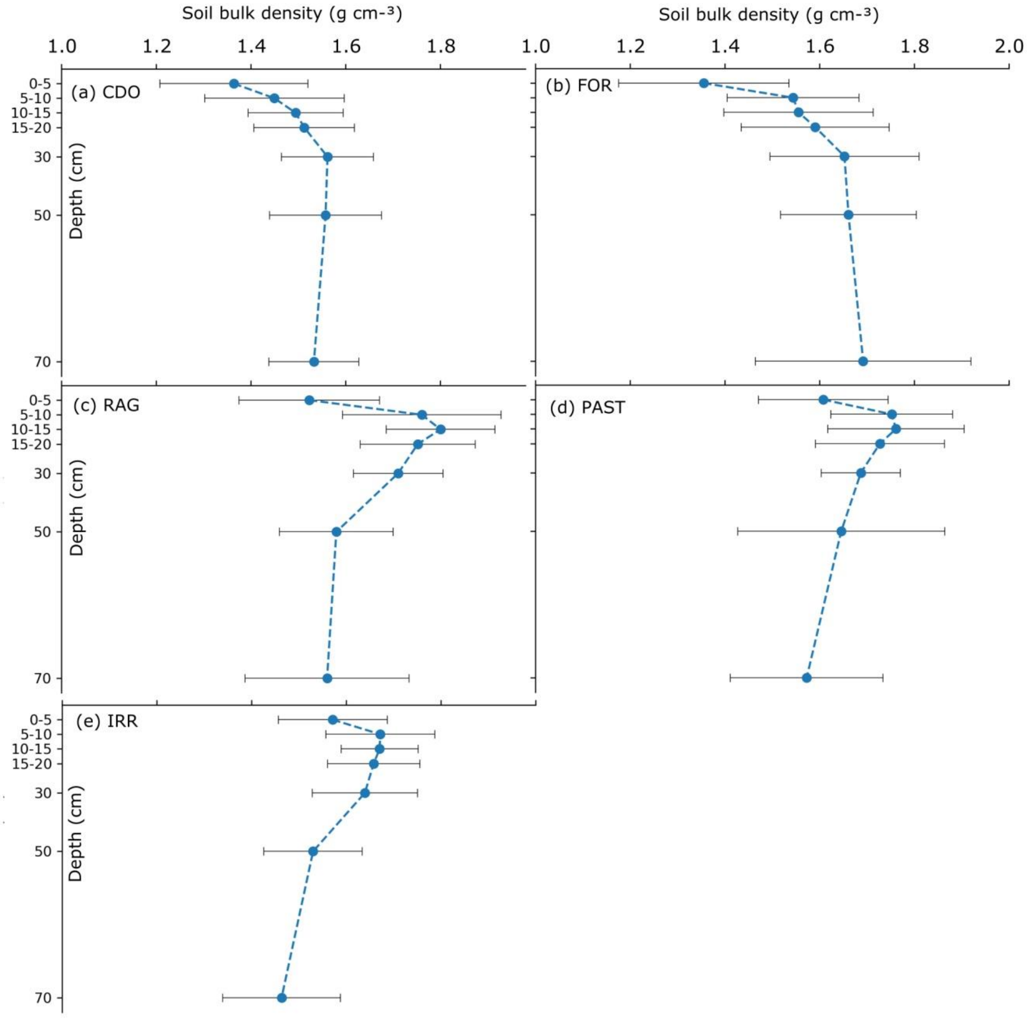


Figure 1.8. Profile average of soil bulk density and standard deviation for different land use and land cover classes. The total samples are 714 distributed in CDO = 22; FOR = 19; IRR = 20; PAST = 21; RAG = 20 areas, multiplied by 7 depths.

Soils under natural vegetation cover had a higher infiltration rates (K_{sat}) compared to managed areas, with mean values of 16.29 cm hour^{-1} for CDO, and 14.47 cm hour^{-1} for FOR, while among the agriculture land uses, average infiltration rates were much smaller, ranging from 3.01 cm hour^{-1} in irrigated croplands to 6.22 cm hour^{-1} in RAG (Table 1.1, Figure 1.7f). The K_{sat} values for 62% of Irrigated areas, 41% of Pasture areas, 29% of Rainfed Agriculture areas, 15% of Forest areas and 5% of the Cerrado areas are lower than 50 mm hour^{-1}, which implies in a runoff occurrence for rainfall above 50 mm hour^{-1}. For rainfall with intensity of 100 mm hour-^{1}, it is expected that surface runoff will occur in 95% of Irrigated areas, 76% of Pasture areas, 62% of Rainfed Agriculture areas, 20% of Forest areas and 32% of Cerrado areas visited (Figure 1.9). Absence of runoff should occur only in cases of rainfall intensity of less than 10 mm hour^{-1}.

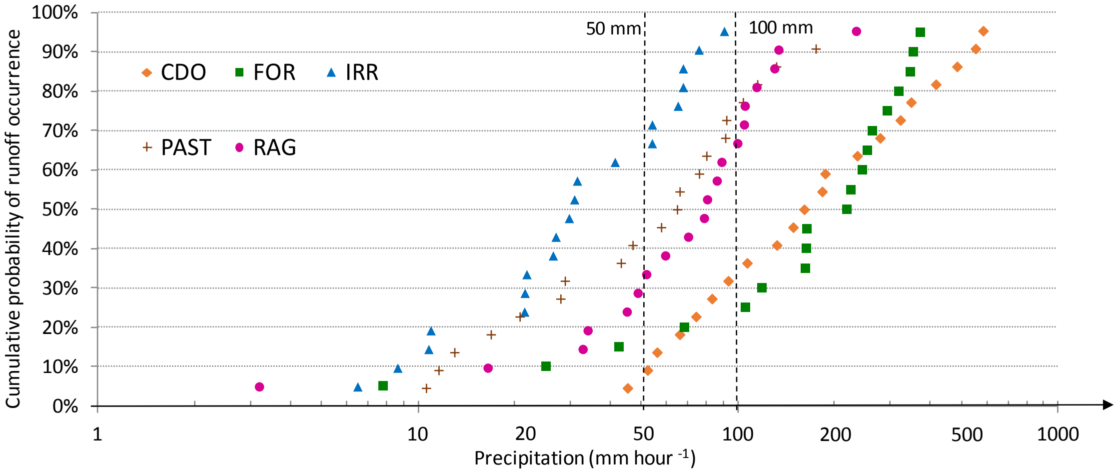


Figure 1.9.Cumulative probability of runoff occurrence for different land use and land cover classes in Western Bahia. Cerrado formations = CDO, Forest Formations = FOR, Rainfed Agriculture = RAG, Irrigated Agriculture = IRR, and Pasture = PAST. The n samples are CDO = 21; FOR = 19; IRR = 20; PAST = 21; RAG = 20.

All LULCCs showed low volumetric water content at the field capacity (-10 kPa), varying from 0.17 cm^3 cm^{-3} to 0.27 cm^3 cm^{-3}. Although LULUCs present different values of field capacity (θ_{fc}) and wilt point (θ_{wp}), the average difference between θ_{fc} and θ_{wp} for each LULCC is typically around 0.06 cm^3 cm^{-3}, highlighting the low water retention capacity for these soils (Table 1.1).

Table 1.1 shows all hydraulic and physical properties for the Campbell and Norman model. Soils under natural vegetation presented lower air entry potential than soils under agriculture or Pasture, with average Ψ_e, values equal to -0.71 kPa for CDO and -0.87 kPa for FOR. The highest values of air entry matric potential were found in soils under Pasture (Ψ_e = -1.80 kPa) and Irrigated Agriculture (Ψ_e = -1.46 kPa), which are associated to higher compaction (Table 1.1, Figure 1.7). The Campbell *b* parameter average values ranged between -4.06 and -5.30, which are similar to literature values for Sandy, Loamy sand and Sandy Loam soils.

Table 1.1. Average and standard deviation for soil physical parameters at 0-5 cm layer under different land use and land cover classes (Cerrado formations (CDO), Forest formations (FOR), Rainfed Agriculture (RAG), Irrigated Agriculture (IRR), and Pasture (PAST).

Parameter	CDO	FOR	IRR	PAST	RAG	unit
Ψ_e	-0.708	-0.868	-1.46	-1.80	-1.20	kPa
std	±0.668	±0.603	±1.27	±1.79	±0.654	
b Campbell	-4.18	-5.10	-4.26	-5.00	-5.30	-
std	±1.20	±2.05	±0.556	±1.66	±1.49	
ρ_a	1.36	1.35	1.57	1.61	1.52	g cm^{-3}
std	±0.157	±0.179	±0.115	±0.138	±0.148	
K_{sat}	16.3	14.5	3.01	5.10	6.22	cm hour^{-1}
std	±0.353	±0.444	±0.332	±0.332	±0.332	
ρ_s	2.53	2.52	2.61	2.58	2.59	g cm^{-3}
std	±0.129	±0.108	±0.070	±0.147	±0.088	
Φ_{tot}	0.481	0.462	0.399	0.376	0.411	cm^3 cm^{-3}
std	±0.136	±0.065	±0.035	±0.045	±0.061	
θ_{fc}	0.1274	0.1789	0.1494	0.1663	0.1719	cm^3 cm^{-3}
std	±0.0527	±0.0913	±0.0442	±0.0608	±0.0477	
θ_{wp}	0.0848	0.1109	0.0858	0.1052	0.1177	cm^3 cm^{-3}
std	±0.0425	±0.0566	±0.0256	±0.0522	±0.0321	
θ_{paw}	0.0425	0.0680	0.0636	0.0611	0.0542	cm^3 cm^{-3}
std	±0.0102	±0.0347	±0.0186	±0.0087	±0.0156	

θ_{fc}: volumetric moisture at -10 kPa; θ_{wp}: volumetric moisture at -1500 kPa, cm^3 cm^{-3}; θ_{paw}: volumetric moisture available to plants.

1.3.2. Pedotransfer functions

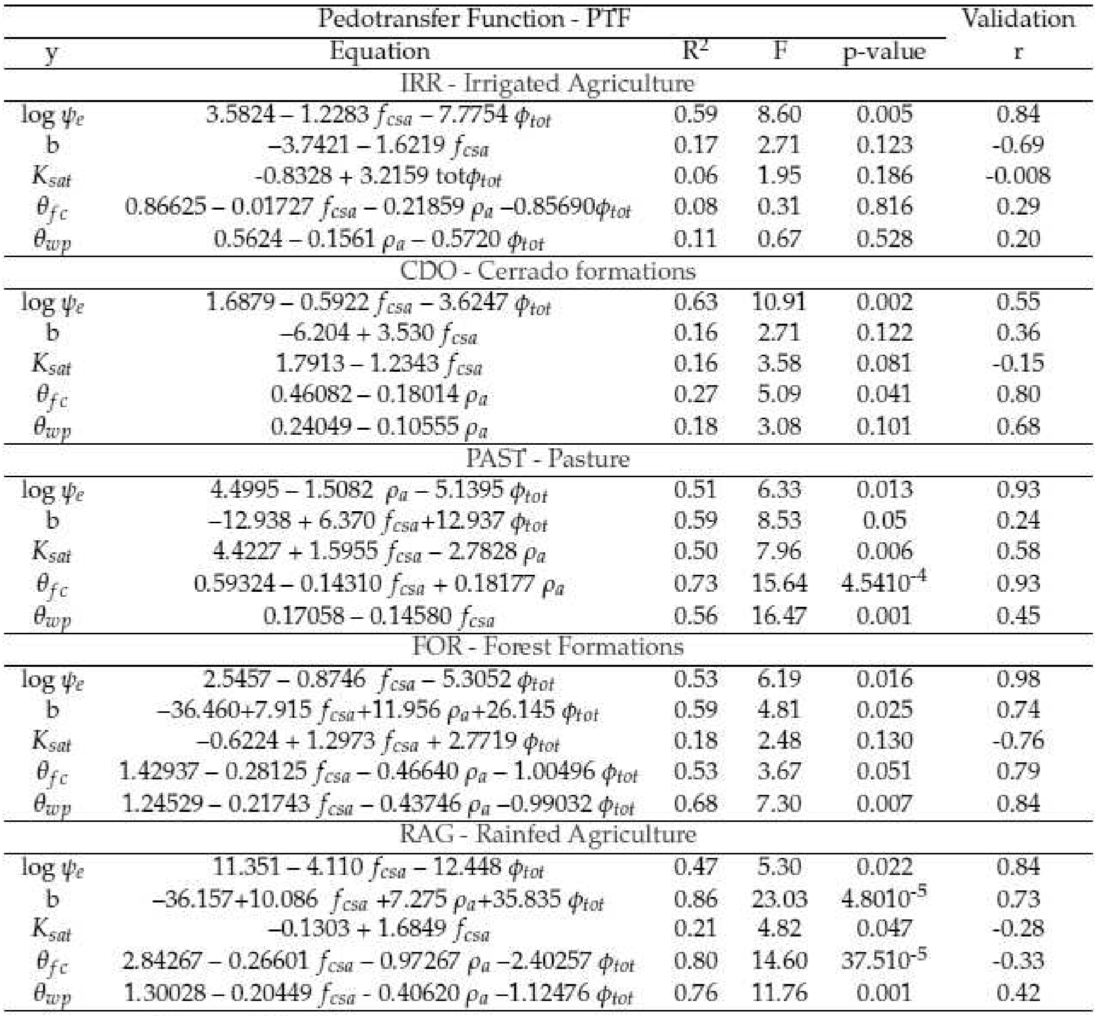
All PTFs used to estimate Ψ_e, b, K_{sat}, θ_{fc}, θ_{paw}, for soils under for PAST and RAG were significant at $\alpha = 0.05$. The PTFs for IRR, CDO, and FOR showed significance only for a few parameters (Table 1.2). Ψ_e was significant in all LULCC, while the b was significant only in FOR, PAST and RAG. The PTFs for K_{sat} were not significant for any LULCCs, except PAST and RAG. θ_{fc} PTFs were significant only for CDO, PAST and RAG, while θ_{wp} PTFs were significant for FOR, PAST and RAG (Table 1.2).

The PTF performance to estimate Ψ_e was generally good, showing the maximum adjustment in FOR areas with r = 0.980, followed by PAST (r = 0.93), RAG (r = 0.84) and IRR (r = 0.84) (Table 1.2, Figure A1). The lowest correlation was found for CDO areas with r = 0.55. For this LUC, the average of $log\Psi_e$ used for calibration and validation were significantly different, which may have contributed to the lower performance in Ψ_e estimate.

For the Campbell b parameter, the performance of the PTF estimative showed poor correlation for CDO, IRR, and PAST, with correlations 0.359, 0.693 and 0.243 respectively (Table 1.2 and Figure A2). However, for RAG and FOR areas, the PTFs showed r > 0.70 of agreement between the estimated and observed Campbell b parameter (Table 1.2).

The soil water content represented by θ_{fc} and θ_{wp} also have a poor correlation for IRR and RAG agriculture land uses with r < 0.20 (Table 1.2 and Figure A4, A5). In the CDO, FOR and PAST, the estimated parameters have a correlation greater than 0.45. The worst correlations were for K_{sat} for all LULCCs, with negative r values, except for PAST (r = 0.58) (Table 1.2 and Figure A3). The adjustments between soil hydraulic parameters observed and simulated for all LULCCs are in the Appendix A.

Table 1.2. Pedotransfer functions for Cerrado formations (CDO), Forest formations (FOR), Rainfed Agriculture (RAG), Irrigated Agriculture (IRR), and Pasture (PAST) areas in Western Bahia.



	Pedotransfer Function - PTF				Validation
y	Equation	R^2	F	p-value	r
	IRR - Irrigated Agriculture				
$\log \psi_e$	$3.5824 - 1.2283\, f_{csa} - 7.7754\, \phi_{tot}$	0.59	8.60	0.005	0.84
b	$-3.7421 - 1.6219\, f_{csa}$	0.17	2.71	0.123	-0.69
K_{sat}	$-0.8328 + 3.2159\, \mathrm{tot}\phi_{tot}$	0.06	1.95	0.186	-0.008
θ_{fc}	$0.86625 - 0.01727\, f_{csa} - 0.21859\, \rho_a - 0.85690\phi_{tot}$	0.08	0.31	0.816	0.29
θ_{wp}	$0.5624 - 0.1561\, \rho_a - 0.5720\, \phi_{tot}$	0.11	0.67	0.528	0.20
	CDO - Cerrado formations				
$\log \psi_e$	$1.6879 - 0.5922\, f_{csa} - 3.6247\, \phi_{tot}$	0.63	10.91	0.002	0.55
b	$-6.204 + 3.530\, f_{csa}$	0.16	2.71	0.122	0.36
K_{sat}	$1.7913 - 1.2343\, f_{csa}$	0.16	3.58	0.081	-0.15
θ_{fc}	$0.46082 - 0.18014\, \rho_a$	0.27	5.09	0.041	0.80
θ_{wp}	$0.24049 - 0.10555\, \rho_a$	0.18	3.08	0.101	0.68
	PAST - Pasture				
$\log \psi_e$	$4.4995 - 1.5082\, \rho_a - 5.1395\, \phi_{tot}$	0.51	6.33	0.013	0.93
b	$-12.938 + 6.370\, f_{csa} + 12.937\, \phi_{tot}$	0.59	8.53	0.05	0.24
K_{sat}	$4.4227 + 1.5955\, f_{csa} - 2.7828\, \rho_a$	0.50	7.96	0.006	0.58
θ_{fc}	$0.59324 - 0.14310\, f_{csa} + 0.18177\, \rho_a$	0.73	15.64	4.5410^{-4}	0.93
θ_{wp}	$0.17058 - 0.14580\, f_{csa}$	0.56	16.47	0.001	0.45
	FOR - Forest Formations				
$\log \psi_e$	$2.5457 - 0.8746\, f_{csa} - 5.3052\, \phi_{tot}$	0.53	6.19	0.016	0.98
b	$-36.460 + 7.915\, f_{csa} + 11.956\, \rho_a + 26.145\, \phi_{tot}$	0.59	4.81	0.025	0.74
K_{sat}	$-0.6224 + 1.2973\, f_{csa} + 2.7719\, \phi_{tot}$	0.18	2.48	0.130	-0.76
θ_{fc}	$1.42937 - 0.28125\, f_{csa} - 0.46640\, \rho_a - 1.00496\, \phi_{tot}$	0.53	3.67	0.051	0.79
θ_{wp}	$1.24529 - 0.21743\, f_{csa} - 0.43746\, \rho_a - 0.99032\, \phi_{tot}$	0.68	7.30	0.007	0.84
	RAG - Rainfed Agriculture				
$\log \psi_e$	$11.351 - 4.110\, f_{csa} - 12.448\, \phi_{tot}$	0.47	5.30	0.022	0.84
b	$-36.157 + 10.086\, f_{csa} + 7.275\, \rho_a + 35.835\, \phi_{tot}$	0.86	23.03	4.8010^{-5}	0.73
K_{sat}	$-0.1303 + 1.6849\, f_{csa}$	0.21	4.82	0.047	-0.28
θ_{fc}	$2.84267 - 0.26601\, f_{csa} - 0.97267\, \rho_a - 2.40257\, \phi_{tot}$	0.80	14.60	37.510^{-5}	-0.33
θ_{wp}	$1.30028 - 0.20449\, f_{csa} - 0.40620\, \rho_a - 1.12476\, \phi_{tot}$	0.76	11.76	0.001	0.42

r: pearson correlation coefficient.

1.4 Discussion

The sand fraction is predominant in the granulometric composition of the soils, the clay content varies between 10% and 41% and the silt fraction presents the lower values, typically below 4% (Figure 1.5 and 1.6). This granulometric composition is the result of the soil source material - in this case, the sandstones of the Cretaceous Urucuia Formation, responsible to origin the sandy soil domain of Cerrado (Jacomine et al., 1976).

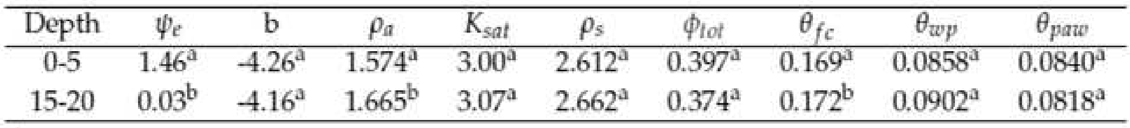
The general trends showed higher values of ρ_a and lower values of Φ_{tot} in agriculture areas compared to native vegetation, revealing that soils under agricultural land use are slightly compacted in Western Bahia. This is in line with Fontana et al. (2016), who found ρ_a in agriculture areas in the region of Luis Eduardo Magalhães equal or above 1.52 g cm^{-3}. Cunha et al. (2001) also found increased ρ_a in different crop areas with different periods of cultivation, demonstrating that duration of land use also have an influence on soil structure. Naturally, the sandy soils of Western Bahia present a sub-surface horizons cohesive (Cunha et al., 2001; Fontana et al., 2016; Giarola et al., 2001; Giarola et al., 2002) which make it more susceptible to compaction by grazing, mechanization and management applied at the soil surface. This transitional or subsurface horizon is observed and characterized by a slight increase in ρ_a, generally, between 10 and 30 cm (Fontana et al., 2016). Indeed, our results show the natural cohesive sub-surface in the CDO and FOR areas (Figure 1.8a-b), and the intensification of the increase of ρ_a in agriculture land uses. The ρ_a in RAG is twice as high in the 10-15 cm layer in relation to the 0-5 cm surface layer. In IRR areas, there is also an increase in ρ_a in these layers, although with less intensity than observed in RAG areas (Figure 1.8).

In Western Bahia, where the Irrigated and Rainfed croplands have a key role in the development of agriculture, this natural sub-surface horizon cohesion may be a concern factor for the maintenance of the rates of infiltration, the permeability and the water availability to the croplands and recharge of the aquifer. In general, the reduction of Φ_{tot}, and the increase of ρ_a may be occurring due to a combination of agricultural implements used to remove the natural vegetation cover and the applied agriculture management, consequently reducing K_{sat} values.

During the fieldwork, the farmers reported that after removing the Cerrado, it is mandatory to use the conventional tillage system, with the plowing complemented by subsoilers and scarifiers, in order to break any physical impediments. According to our interviews, after conventional tillage, the no-tillage is applied during four years, and in the fifth year the conventional tillage system is used again, characterizing a mixed management. However, the lack of sufficient long-term data hampered any claim that this management is the best practice to adopt in order to avoid cohesive sub-surfaces (Stone et al., 2001; Santos et al., 2011), but the effects of surface and subsurface compaction in hydraulic properties in IRR areas (Table 1.3). In these areas, where there are two or more crops planted per year, and the traffic of machinery is more intense, ρ_a at the 15-20 cm layer is 1.67 g cm^{-3}, significantly higher than at the surface (0-5 cm) layer (1.57 g cm^{-3}) (Table 1.3), which is a vertical pattern similar to all the other LULCCs (Figure 1.8). While the difference in ρ_a between surface and subsurface layers is significant, it is not sufficient to influence the hydraulic parameters, such as K_{sat}, ϕ_{tot}, θ_{fc} and θ_{wp} (Table 1.3), although Ψ_e and θ_{fc} are significantly different in the vertical.

The spatial variability of K_{sat} in soils under natural vegetation is also extremely high. In the CDO, K_{sat} varies between 4.5 cm hour^{-1}and 58.5 cm hour^{-1}, while in FOR it varies between 0.78 cm hour^{-1}and 37.67 cm hour^{-1}. For Cerrado areas in the MATOPIBA, other studies have found K_{sat} in the range between 5.26 cm hour^{-1} (Filizola et al., 2017) and 403.8 cm hour^{-1} (Fontana et al., 2016).

Table 1.3. Hydraulic and soil physical properties for irrigated land use in different depths. $\square_e$: soil air potential entry; kPa, b: Campbell parameter; ρ_a : soil bulk density; g cm^{-3}, ρ_s: soil particle density; g cm^{-3}, Φ_{tot}: total porosity; fraction, K_{sat}: saturated hydraulic conductivity; cm hour^{-1}, θ_{fc}: volumetric moisture at -10 kPa; cm^3 cm^{-3}, θ_{wp}: volumetric moisture at -1500 kPa, cm^3 cm^{-3}; θ_{paw}: volumetric moisture available to plants in cm^3 cm^{-3}.



Depth	ψ_e	b	ρ_a	K_{sat}	ρ_s	ϕ_{tot}	θ_{fc}	θ_{wp}	θ_{paw}
0-5	1.46^a	-4.26^a	1.574^a	3.00^a	2.612^a	0.397^a	0.169^a	0.0858^a	0.0840^a
15-20	0.03^b	-4.16^a	1.665^b	3.07^a	2.662^a	0.374^a	0.172^b	0.0902^a	0.0818^a

*Values significantly different according to the t Student test at $\alpha = 0.05$ are followed by different letters.

In this study, the variability of K_{sat} in the natural areas can be explained by the higher heterogeneity of the soils, and, consequently, different accumulation of organic matter, litter, tree density, the soil fauna, source material and root systems acting on the soils structures. Although the soil compaction, the average K_{sat} for agriculture areas still can be considered higher when compared to K_{sat} for latossolos under conventional tillage system in Goiás, $K_{sat} = 0.535$ cm hour^{-1} (Silva et al., 2014). For other agriculture areas, in the Cerrado biome, the K_{sat} values presented in the literature ranges between 5.41 cm hour^{-1} (Filizola et al., 2017), and 15.47 cm hour^{-1} (Fontana et al., 2016). Likely, the use of rotation between maize, soybean, cotton and other croplands, in addition to the mixed management in Western Bahia, contribute to the maintenance of the high rates of K_{sat} in agriculture land uses areas even with the presence of soil compaction. However, there is necessity to monitor the decreasing infiltration capacity, once its intensive agriculture land use decreases this capacity and increases the chances of erosion.

1.5. Conclusion

This study analyzes hydraulic and physical soil properties in Western Bahia at a local scale and in different land uses and land covers. Significant changes were found between some soil properties in agricultural areas and natural vegetation cover, indicating that agricultural activity can influence the soil properties.

The agriculture land use increased soil bulk density at soil surface and subsurface, reducing the K_{sat} by an order of magnitude in relation to Cerrado and Forest areas, and also decreasing the soil porosity. Despite the reduction, K_{sat} range between 30 and 62 mm hour^{-1}, which are still considered high hydrological infiltration rates. For rainfall with intensity of 50 mm hour^{-1}, surface runoff is expected in 65% of Irrigated areas, 43% of Pasture areas, 30% of Rainfed Agriculture areas, 16% of Forest areas and 5% of the Cerrado areas visited. For rainfall with intensity of 100 mm hour^{-1}, it is expected that surface runoff will occur in 100% of Irrigated areas, 76% of Pasture areas, 65% of Rainfed

Agriculture areas, 21% of Forest areas and 33% of Cerrado areas visited. Absence of runoff should occur only in cases of rainfall intensity of less than 10 mm hour^{-1} or less. Thus, our results reveal that in Western Bahia the agriculture land use areas do not affect directly the water vertical flow for visited areas, but in case of very intense precipitation events, the K_{sat} reduction may lead to erosive processes favoring nutrient and soil losses. In Western Bahia, however, there are some farmers interested in adopting sustainable practices that preserve the soil quality, investing in state-of-the-art technology, increasing the intervals of soil revolving and implementing crop rotation system.

Nonetheless, these results cannot be extrapolated for all Western Bahia. It is still unknown how the Irrigated, Rainfed Agriculture, and Pasture, influence the hydraulic and physical properties in the long-term, and how the management (conventional tillage or no-tillage) can influence these properties in loamy/sand soils.

In the literature, several studies that monitor physical soil properties show that reduced tillage practices have promising results for soil moisture conservation and for crops growth. However, the number of scientific studies remains low for the sandy soil domain of Cerrado agricultural frontier. We emphasize that the impacts of land use change on hydraulic and physic soil properties are a reality in MATOPIBA and there is an urgent need to monitor how these changes occur over time in order to develop effective mitigation strategies of soil and water conservation.

CHAPTER 2. CARBON DYNAMICS AT A SANDY SOIL DOMAIN OF A CERRADO AGRICULTURE FRONTIER

2.1 Introduction

Native vegetation suppression to implement of agriculture use is considered the major source of greenhouse gas (GHG) emissions to the atmosphere in Brazil (Leite et al., 2011; Calvin et al., 2016, SEEG, 2018). In 2016, agricultural activities alone represented 74% of Brazilian GHG emissions, from which almost two thirds come from natural vegetation conversion to agriculture and pasture, while the rest comes from direct agriculture emissions, such as enteric fermentation and soil management (SEEG, 2018).

Although Amazonia presents high deforestation rates they have been lower in relation to the suppression of Cerrado native vegetation in the last years: in 2015, this rate in Cerrado was 52% higher than in the Amazon (MMA, 2017). This fact is result of the development of the largest and most dynamic agricultural frontier in the Brazilian Cerrado domain, known as MATOPIBA (acronym for the states Maranhão, Tocantins, Piauí and Bahia).

The emergence of MATOPIBA is associated to historical facts, and partially to scientific and technological advances achieved by the agricultural sector. The technological advances allowed the management and the application of specific techniques of sandy soils of Cerrado such as liming (correction of acidity through limestone), phosphate fertilization, and potassium fertilization. Until 1930s, the Cerrado biome was little used for agriculture because of its was considered as unproductive lands, specially because the seasonal climate and acid and nutrient-poor soils. This scenario changed in 1970s, when the region begin to be intensively exploited due to depletion of Brazilian South and Southeast land available for agricultural occupation, the need to increase of agricultural production, and government incentives for regional development programs.

The Cerrado soils in Brazilian Central West (States of Goiás, Mato Grosso and Mato Grosso do Sul), were the first to be occupied and used for livestock, and after to agriculture. In Central West, the climate is effectively humid tropical (Aw) according Koppen Classification, and soils are predominant Latossols (Oxisols) with medium or clayey texture.

After the saturation of Brazilian Central West lands, the agricultural practices migrated to north of Cerrado biome and developed under sandy soil domain of Cerrado, giving origin to the last agricultural frontier of the country MATOPIBA. In MATOPIBA, the Western Bahia stands out by the agricultural expansion. In 2017, the planted area were 1.60 million of hectares of soybean and 321,000 hectares of soybean cotton, reaching high productivity records, with an average of 6 million tons of soybean and 1.245 million tons of cotton in the 2017/2018 harvest (AIBA, 2017).

Although Western Bahia have predominance of Cerrado sandy soils, it is located on the Urucuia Aquifer, with high water availability and natural resources. The abundance of natural resources in this region and the continuous expansion of agribusiness bring a major concern about the regional water availability and direct carbon emissions from agricultural activities on Cerrado biome (Spera et al., 2016; Oliveira et al., 2017; Nunes et al., 2017).

Estimates showed that the native vegetation suppression emitted nearly 200 Tg-C between 2003 and 2008 in case of replacement by pasture (Bustamante et al., 2012), and an average of 179 Tg-C between 2003 and 2013 from natural vegetation conversion to agriculture (Noojipady et al., 2017). To avoid the increasing of direct and indirect carbon emissions and reduces the amount of carbon emitted from agricultural practices, different carbon dioxide removal (CDR) practices have been recommended by Intergovernmental Panel on Climate Change- IPCC.

The soil management is one key practices to enhancement of long-term carbon sequestration by soil. Practices like no-tillage (NT), crop rotation, and integrated crop-livestock are examples of CDR practices that may reduce the carbon losses. The choice of which management technique will be applied to the soil is essential to determine if agricultural activities are a sink of carbon (Guo and Gifford, 2002; Cerri et al., 2008; Tivet et al., 2013; Sá et al., 2013; Fujisaki et al., 2015), or a source to atmosphere (Maia et al., 2010; Don et al., 2011; Sá et al., 2013; Durigan et al., 2017). Besides management soil, the climate, vegetation cover, drainage, and the intrinsic soil properties such as texture, mineralogy, and structure are determinant factors to enhancement or depletion of soil carbon stock.

Increase the amount of soil carbon is a challenge in regions under seasonal climate and with lower clay content into soils as Cerrado domain. The seasonality of climate associated to high sand fractions hinder the use of cash or cover crops and the low clay concentration decreases the resilience of organic matter, which under high temperatures is easily lost by the surface soils.

The knowledge about the how land use changes may affect the soil carbon sequestration in a sandy soil Cerrado domain is particularly important to recommend the effective CDR practices that increase the soil carbon stocks in the agriculture areas, and contributes to removal of carbon emissions by agriculture sector.

In this context, and considering the current global climate change scenario, it is extremely relevant to quantify the sources and sinks of carbon in a sandy soil domain located on the largest and most dynamic agricultural frontier in Brazil in order to provide basis for the development of climate change mitigation and food security policies. The main objective of this study is to evaluate how the regional land use change affects the soil carbon stocks at a sandy soil domain of a Cerrado agricultural frontier in Brazil – Western Bahia, and to reconstruct the historical carbon balance considering the 1990-2018 period for this region, which is considered the largest and most productive area of MATOPIBA.

2.2 Methods

2.2.1 Study area

The study area is the Western Bahia region, located at the most dynamic agriculture frontier in the Cerrado biome. A description of the region and a figure with soil sampling sites are presented in Chapter 1, Section 1.2 and Figure 1.3, respectively.

2.2.2. Soil carbon stock sampling design

Soil samples were collected in two field campaigns throughout 2017 for same five Land Use and Land Cover Classes (LULCCs): (1) Cerrado formations (CDO), (2) Forest formations (FOR), (3) Rainfed agriculture (RAG), (4) Irrigated agriculture (IRR) and (5) Pasture (PAST) described in Chapter 1.All IRR samples were collected in the middle of the crop cycle during July 2017, while samples of other LULCCs were collected during November and December of 2017, at the beginning of the rainfed crop cycle.

The sampling points for each LULCC were determined using the following criteria: opening year of agriculture or Pasture area between 1990 and 2017, and logistic access to farms, including road conditions and permission to enter the farm by the farmers.

In total, 1400 soil samples (700 undisturbed and 700 disturbed samples) were collected considering 5 LULCCs × 20 sample points × 7 depth levels. At each sampling point, samples were collected at the depths 0-5, 5-10, 10-15, 15-20, 20-40, 40-60 and 60-100 cm. For the last three soil depths, layers were considered homogeneous and samples were collected in the middle of the layer at 30, 50 e 70 cm, respectively. The disturbed samples were composed by 3 sub-samples collected as described in Figure 2.1.

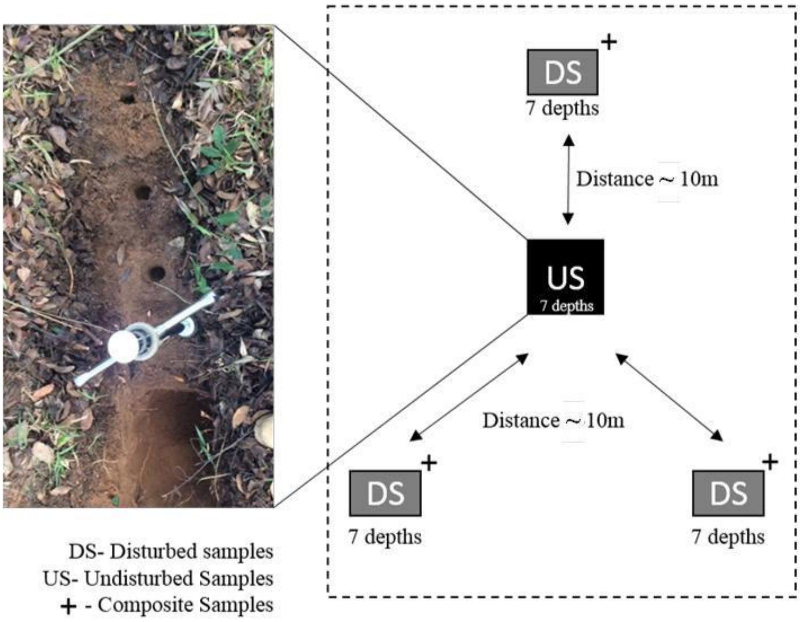


Figure 2.1. Sampling soil design used in this study during the field work.

The 700 undisturbed samples were used to calculate the soil bulk density (ρ_a, g cm^{-3}), while the 700 disturbed samples were used to estimate soil organic carbon concentration (SOCC, g kg^{-1}). The ρ_a and the SOCC analyses were carried out at the CAMPO laboratory (Paracatu, MG) using the volumetric ring method (Blake and Hartge 1986) and colorimetric Walkey Black method (Walkey and Black, 1934).

Both ρ_a and SOCC were used to estimate the soil carbon stocks (C_S) for each soil layer by multiplying the SOCC and ρ_a by the thickness of the layer. For soil profile, the equivalent mass method of Ellert and Bettany (1996) was used to calculate the Soil Carbon Stock – SCS_Z. In this method, the soil carbon stock is calculated considering the amount of mass in a reference soil (natural land cover), in order to remove possible effects of soil compaction in the agricultural systems, avoiding overestimates of carbon soil in the surface layers. This method is mathematically described by Equation 2.1, and the reference soil was the CDO soil.

$$SCS_z = \sum_{i=1}^{n-1} C_{ti} + \left[M_{tn} - \left(\sum_{i=1}^{n} M_{ti} - \sum_{i=1}^{n} M_{si}\right)\right] \times C_{tn} \qquad (2.1)$$

where SCS_z is the total C stock (Mg-C ha^{-1}) in soil to a depth z equivalent to the same mass of soil as that in the reference profile, $\sum_{i=1}^{n-1} C_{ti}$ the sum of total carbon content (Mg-C ha^{-1}) in the layers 1 (surface) to layer n-1 (penultimate) in the treatment profile, $\sum_{i=1}^{n} M_{si}$ the sum of the mass of soil (Mg ha^{-1}) in layers 1 (surface) to n (greatest depth) in the reference soil profile, $\sum_{i=1}^{n} M_{ti}$ the sum of the mass of soil (Mg ha^{-1}) in layers 1 (surface) to n (greatest depth) in the treatment profile, M_{tn} the mass of soil in the deepest layer in the treatment profile and C_{tn} the concentration of carbon (Mg C Mg^{-1}) in the deepest layer in the treatment profile. In this thesis, SCS_z was calculated for the layers SCS_z(0-30 cm), SCS_z(0-60 cm), and SCS_z(0-100 cm) depths.

The Student´s t test was used to evaluate differences between SCS_{30}, SCS_{60} and SCS_{100}, in different LULCCs, and the Tukey-Cramer test used to compare C_s differences among LULCCs considering $\alpha = 0.05$. Descriptive statistics (mean and standard deviation and confidence interval) were also calculated.

2.2.3 Land use and land cover databases

The concept of Land Cover (LC) refers to the surface cover on the ground (for example: vegetation, urban infrastructure, water or bare soil), while Land use (LU) refers to the purpose the land serves (for example: recreation, wildlife habitat, or agriculture).

In this study, I used three agriculture LUs and two native vegetation LCs to evaluate the AboveGround Biomass (AGB), BelowGround Biomass (BGB), C_S, SCS_{30}, SCS_{60}, SCS_{100} and Total Carbon Stock ($\text{TCS} = \text{AGB} + \text{BGB} + \text{SCS}_{100}$). These five

LULCCs were associated to classes available in classification map dataset – OBahia (Table 2.1) for the SCS_{100} historical reconstruction.

The OBahia land use and land cover classification has nine land use classes: Forest Formations (FF), Savanna Formations (SF), Grasslands Formations (GF), Agriculture or Pasture ($RAG/PAST_C$), Rainfed Agriculture (RAG_C), Irrigated Agriculture (IRR_C), Pasture ($PAST_C$), water bodies and urban areas/farm buildings at the scale of 1:15,000 (30 m spatial resolution). This database was developed by filtering the Landsat 5, 7 and 8 satellite image collections for the dry period of the Cerrado (04/April to 30/September) for each year from 1990 to 2018, and selected the median of each pixel. The LULCC description of the 102 sites that I visited in Western Bahia during fieldwork in 2017 was used to select training regions to the machine-learning algorithm. After the initial learning, LULCC were classified through the Random Forest classifier in the Google Earth Engine platform. The results of this classification show the trends of agricultural use in the region over time and with an accuracy of 90%, thus being appropriate for this work. Data are available at: http://obahia.dea.ufv.br.

Table 2.1. Land Use and Land Cover Classes from soil carbon stock sampling design

	Land Use and Land Cover Classes used to soil carbon stock sampling design LULCCs	**Correspondent Land Use and Land Cover Classes from OBahia maps**
1	**FOR-** Forest Formations	**FF-** Forest Formations
2	**CDO-** Cerrado Formations	**SF-** Savanna Formations **GF-** Grasslands Formations
3	**RAG-** Rainfed agriculture	**RAG$_C$-** Rainfed agriculture
4	**IRR-** Irrigated agriculture	**IRR$_C$-** Irrigated agriculture
5	**PAST-** Pasture	**PAST$_C$-** Pasture
6	**RAG/PAST**- Rainfed agriculture or Pasture	**RAG/PAST$_C$-** Rainfed agriculture or Pasture
7	Carbon content not sampled. Assumed to be zero	Water bodies
8		Urban areas/farm buildings

Therefore, in this study, natural land cover is represented by FOR – Forest Formations, and CDO – Cerrado formations, with the latter sub-divided in: Savanna Formations – SF and Grasslands Formations – GF covers (Table 2.1). The vegetation cover in SF is predominantly formed by shrubs and trees, while grasses are predominant in the GF vegetation cover (Table 2.1). The agriculture land uses are divided in Rainfed agriculture (RAG$_C$), Irrigated agriculture (IRR$_C$), Pasture (PAST$_C$) and Agriculture or Pasture (RAG/PAST$_C$).

2.2.4. Native vegetation spatial carbon stocks - Aboveground and Belowground biomass and soil carbon stocks

The methodology employed to develop the native vegetation map is similar to the one used by Dias et al. (2017), who used different databases to produce a native vegetation biomass map for Brazil.

The vegetation map produced by RadamBrasil project and the vegetation map produced by the environmental institute INEMA (*Instituto do Meio Ambiente e Recursos Hídricos*) were used to develop the native vegetation map for Western Bahia, and subsequently, to develop AGB, BGB, and SCS_{100} maps (Figure 2.2).

First, the natural vegetation classes produced by INEMA were maintained and the classes associated with "anthropic areas" were replaced by natural RadamBrasil vegetation classes. Where both maps presented antropic areas, I reclassified the class using the criteria of proximity to nearby preserved areas in the Technical Manual of Vegetation of IBGE (IBGE, 2012). At the end of the fusion of vegetation maps, the native vegetation map was composed by 16 predominant natural physiognomies (Step 1, Figure 2.2). This method to develop a native vegetation map introduces uncertainties, as different physiognomies may occur in large polygons, especially in a biome characterized by a mosaic of physiognomies like Cerrado.

In addition to the uncertainties regarding AGB and BGB estimate, it was necessary to consider that the biomass value was homogeneous for all pixels with the same vegetation class, differently to the natural environment where the ABG and BGB for same physiognomy vary according the biotic conditions as the season of the year (solar radiation, pluviometric regime), and soil types and fertility.

Each pixel (30 m) received an average AGB and BGB according to physiognomy defined in this vegetation map (Step 2, Figure 2.2). The AGB values for Cerrado physiognomies were obtained from the available literature (Appendix A1). In most cases, the uncertainty associated to the methods (experiment design) and biomass computation (alometric equation or remote sensing) used to AGB and BGB estimates were not provided, which makes it impossible to assign values to the AGB and BGB maps. The lack of uncertainty measurement of AGB and BGB also affected National reports such as the Third Edition of the Annual Estimates of Greenhouses Gas Emissions Report published in 2015, which presents a single AGB or BGB value for that physiognomy in all Cerrado or state limits.

Currently, the estimate AGB from remote sensing is available only for forests physiognomies and does not cover areas with low biomass plants like shrub and grasses.

The SCS map was developed using the estimate of SCS_{100} for natural vegetation areas obtained by fieldwork. For this, the bootstrap technique was applied to the samples to produce thousands of random estimates of soil carbon stocks samples. Then, a Monte Carlo simulation generated random SCS_{100} values assigned to each pixel of the map for Forest formations or Cerrado formations, according to the physiognomy in the native vegetation map (Step 3, Figure 2.2). The uncertainties of SCS_{100} estimate for all LULCCs are part of the results of this thesis and are presented in Table 2.2.

The results of steps 1, 2 and 3 in Figure 2.2 are maps of AGB, BGB and SCS_{100} for natural vegetation. These maps were used as input to the Western Bahia Carbon Model (WBCM) to reconstruct stocks and balance, described in the next section.

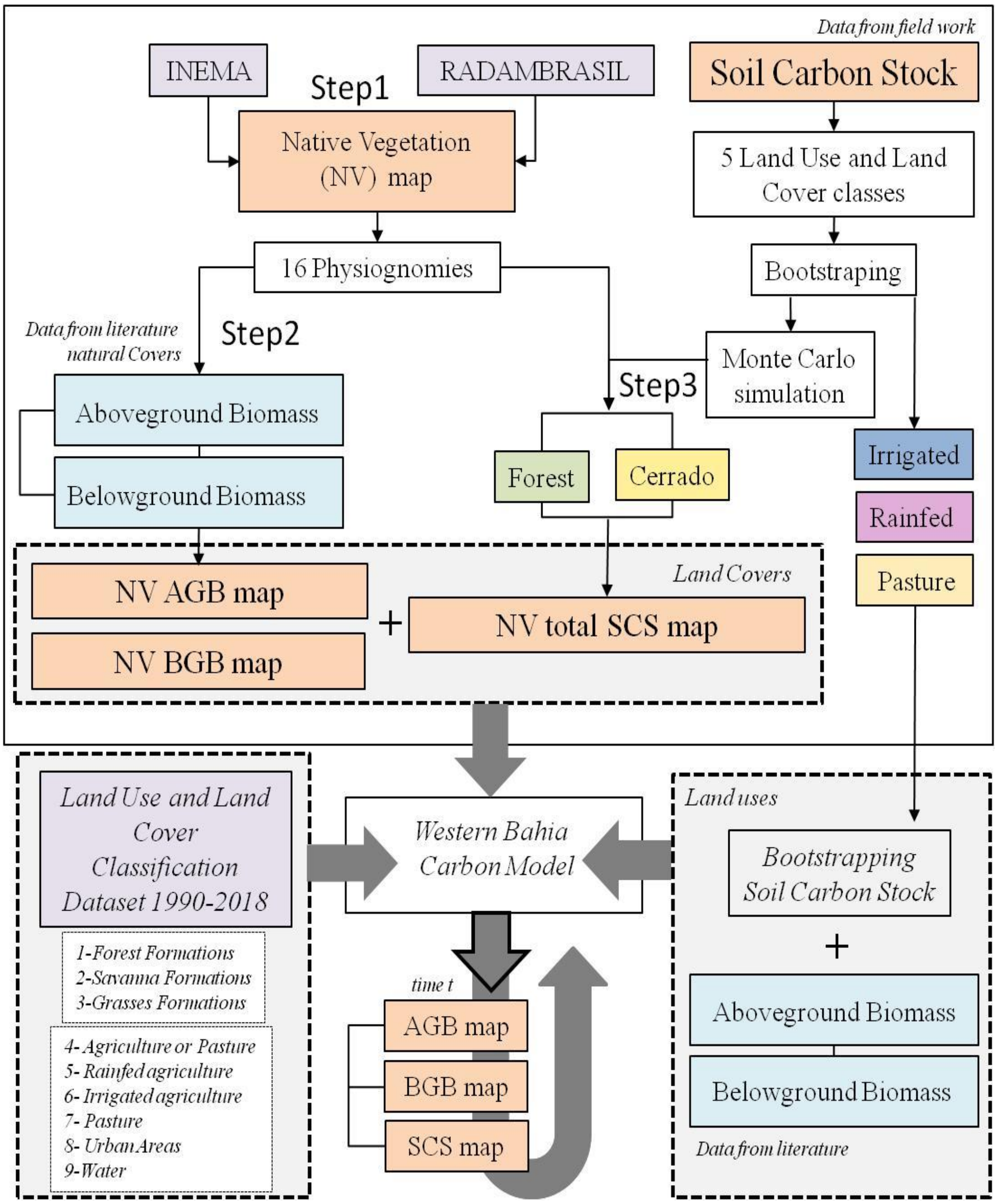


Figure 2.2. Development processes for Aboveground, and Belowground Biomass and Soil Carbon Stocks maps for Western Bahia.

2.2.5 Carbon Stocks Historical Reconstruction (1990-2018)

The carbon stock historical reconstruction was calculated using a simple bookkeeping model, the Western Bahia Carbon Model (WBCM). A bookkeeping model tracks changes in carbon stocks from year to year rather than trying to model the individual biological processes that constitute the carbon balance, i.e. photosynthesis and respiration (Moore et al. 1981). The WBCM uses the land cover classification dataset from OBahia (Section 2.2.3) and the native vegetation AGB, BGB and SCS maps (developed in Section 2.2.4) as inputs.

The first step to historical carbon reconstruction is to provide the AGB, BGB and SCS maps for the first year of period (1990). For this, the WBCM inputs native vegetation AGB, BGB and SCS_{100} and the OBahia LULCC for 1990 (Figure 2.2). Then, the model assigns these values to each LULC class, producing, AGB, BGB and SCS_{100} maps for 1990. The model follows the same procedure to generate a new map for the subsequent years. If there were no changes between $OBahia_{t-1}$ and $OBahia_{t}$ classes, then the native vegetation values of AGB. BGB and SCS_{100} values are maintained. Otherwise, if changes are detected, each pixel receives a new AGB, BGB, and SCS_{100} values according the reference value from Table 2.2. For SCS_{100}, the new values came from the Monte Carlo simulation applied to the observed data for different LULCCs. Finally, at the end of each year, the WBCM writes the ABG, BGB, and SCS_{100} map in Mg-C ha^{-1} (Figure 2.2).

The lack of knowledge about long-term carbon annual gains or losses on the ABG, BGB and SCS_{100} for each LULCCs limited the use this variability in the carbon reconstruction maps. Thus, this model assumes that (1) AGB, BGB and SCS_{100} for CDO and FOR are at an equilibrium state, (2) no changes occurred in the last 28 years on the soil carbon stocks for natural land covers, (3) the croplands in IRR and RAG areas are annual croplands, which maintained the AGB, (4) there are no interactions between the carbon reservoirs. These are classical assumptions in bookkeeping models.

Table 2.2. Parameters for Forest Formations (FF), Savanna Formations (SF), Grasslands Formations (GF), Crop or Pasture (RAG/PAST), Rainfed Crop (RAG), Irrigated Crop (IRR), Pastureland (PAST) used to Carbon Stock Historical Reconstruction for Western Bahia.

OBahia classes	Parameter description	value	Reference
	Aboveground biomass in Mg ha^{-1}		
FF	Reference value of AGB for FF	36.7	Table B1
SF	Reference value of AGB for SF	26.4	Table B1
GF	Reference value of AGB for GF	6.57	Table B1
RAG$_{\mathrm{C}}$	Reference value of AGB for soybean	7.04	Cruz et al. (2010)
IRR$_{\mathrm{C}}$	Reference value of AGB for crops	8.5	Cruz et al. (2010)
PAST$_{\mathrm{C}}$	Reference value of AGB for Pasture	1.28	Santos (2007)
RAG/PAST$_{\mathrm{C}}$	Reference value of AGB for RAG, IRR, PAST	5.49	Average of RAG,IRR, PAST
	Belowground biomass in Mg ha^{-1}		
FF	Reference value of BGB for FF	11.1	Table B1
SF	Reference value of BGB for SF	10.8	Table B1
GF	Reference value of BGB for GF	13.5	Table B1
RAG$_{\mathrm{C}}$	Reference value of BGB for soybean	3.52	Cruz et al. (2010)
IRR$_{\mathrm{C}}$	Reference value of BGB for crops	3.4	Cruz et al. (2010)
PAST$_{\mathrm{C}}$	Reference value of BGB for Pasture	5.41	Santos (2007)
RAG/PAST$_{\mathrm{C}}$	Reference value of BGB for RAG, IRR, PAST	4.11	Average of RAG, IRR, PAST
	Soil Carbon Stock (0-100 cm) in Mg-C ha^{-1}		
FF	SCS for FOR	82.5 ± 43.6	Result of this thesis. Table 2.3
SF	SCS for CDO	70.3 ± 41.6	
GF	SCS for RAG	57.4 ± 33.3	
RAG$_{\mathrm{C}}$	SCS for IRR	78.1 ± 25.5	
IRR$_{\mathrm{C}}$	SCS for PAST	51.7 ± 25.5	
PAST$_{\mathrm{C}}$	SCS for RAG, IRR, PAST	62.4 ± 28.1	

2.2.6 Trends on Carbon Stocks

The spatial patterns of AGB, BGB and SCS$_{100}$ for 1990, 1997, 2004, 2011 and 2018 and the absolute values of total carbon stocks are calculated. The percentage rates of AGB, BGB, SCS$_{100}$ and TCS for 1997, 2004, 2011 and 2018 in relation 1990 are also presented to improve the description and discussion of results.

2.2.7 Uncertainty language

The assessments of the Intergovernmental Panel on Climate Change (IPCC), since the First Assessment Report, have involved calibrated uncertainty language and other methods aiming towards clear communication of the degree of certainty in findings of the assessment process (IPCC, 2013). In this thesis, I consider the uncertainties guidance provided to author teams of the Fifth Assessment Report (AR5) to classify the range of uncertainty, using the following likelihood statements:

- Virtually certain, for $\alpha \leq 0.01$
- Extremely likely, for $\alpha \leq 0.05$
- Very likely, for $\alpha \leq 0.10$
- Likely, for $\alpha \leq 0.333$
- More likely than not, for $\alpha < 0.50$
- Unlikely, for $\alpha \geq 0.666$
- Extremely unlikely, for $\alpha \geq 0.95$

2.3. Results

2.3.1 Soil carbon stock in Western Bahia – observed data

The estimation of soil carbon stock C_S per layer followed the soil organic carbon concentration trends (Table C1), decreasing C_S through the soil profile (Figure 2.3). At the 0-5 cm layer, C_S values for IRR and FOR areas were not statistically different ($\alpha = 0.05$). Values of CDO, PAST and RAG, are not statistically different ($\alpha = 0.05$) according to the Tukey-Cramer test. However, IRR and FOR areas are statistically different from CDO, PAST and RAG (Figure 2.3a). At the 5-10 cm layer, there are no statistical differences among the CS in IRR, PAST, CDO and RAG at $\alpha = 0.05$, while the only significantly different C_S in this layer was between FOR and PAST, CDO and RAG areas (Figure 2.3b). At the 10-15 cm layer, CS was only statistically different between PAST and FOR areas (Figure 2.3c). No statistical differences ($\alpha = 0.05$) were found across the LULCCs for layers below 15 cm (Figure 2.3d-g).

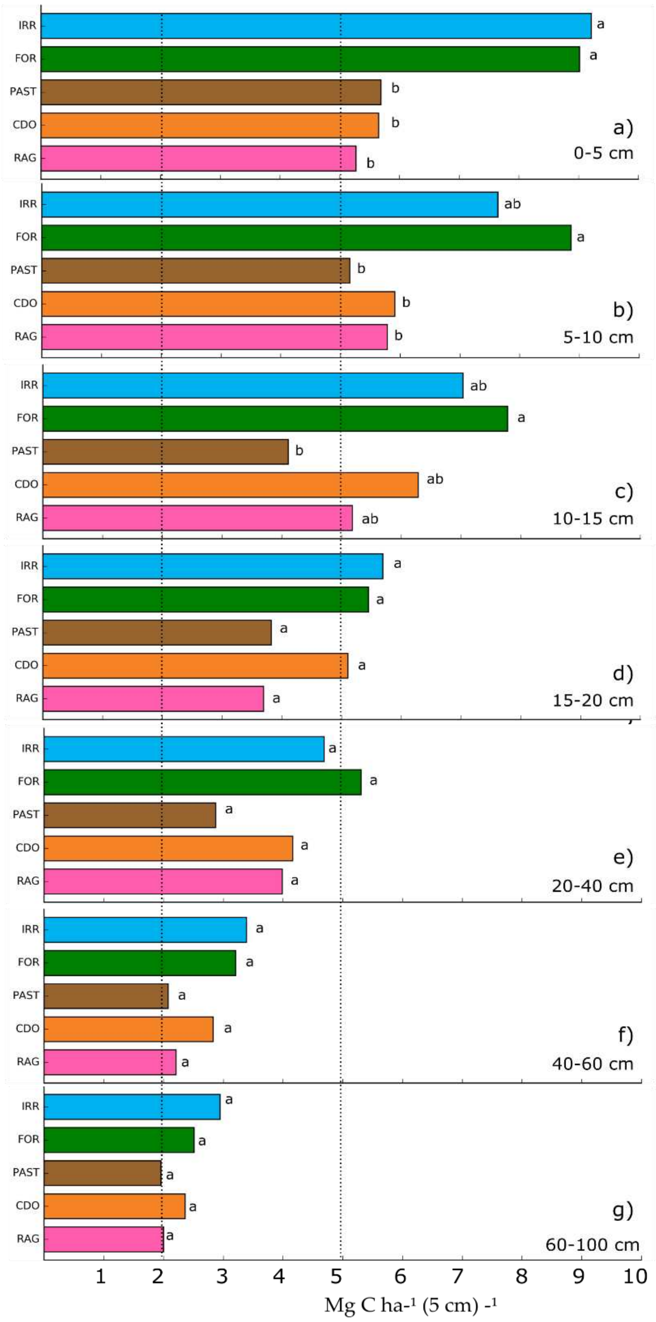


Figure 2.3. Soil carbon stock for different depths (C_S) and different LULCCs (CDO = Cerrado Formations, FOR = Forest Formations, RAG = Rainfed Agriculture, IRR = Irrigated Agriculture, PAST = Pasture) in Western Bahia. The C_S presented corresponds the amount of carbon in the five centimeters of layer thickness. C_S followed by different letters are statistically different at $\alpha = 0.05$ according Tukey-Cramer test.

The average, standard deviation and confidence interval for SCS_{30}, SCS_{60} and SCS_{100} values for each LULCC are presented in Table 2.3. The SCS_{30} and SCS_{100} differences between agricultural LU and native vegetation covers are presented in Table 2.4, while the average comparisons are presented in Table 2.5.

It is extremely likely that replacement of FOR areas by RAG or PAST considering the SCS_{30}, and the replacement of FOR areas by PAST in SCS_{100} decreases the amount of soil carbon stocks and that it is very likely that the SCS_{100} decreases if FOR areas is replaced by RAG. Comparing the SCS between soil natural cover (CDO and FOR) and the IRR, it is more likely than not that there are no differences between IRR and FOR or CDO considering 0-30 cm layer, and when IRR is replaced by CDO considering 0-100 cm. Between FOR and IRR, it is unlikely that there is an decrease in SCS_{100}.

The average of SCS_{30} for FOR, IRR and CDO areas presents the higher amount of SCS_{30} compared to other LULCCs, with 51.0 ± 25.9 Mg-C ha^{-1}, 45.5 ± 11.4 Mg-C ha^{-1} and 40.1 ± 23.3 Mg-C ha^{-1} (average followed by standard deviation), respectively (Table 2.3). In RAG and PAST, SCS_{30} is 32.3 ± 20.4 Mg-C ha^{-1} and 28.0 ± 11.4 Mg-C ha^{-1}, respectively. These results show that the higher SCS_{30} losses in the top soil occurs when FOR or CDO areas are replaced by PAST practices, reducing the SCS_{30} by -82.1% and -43.1%, respectively (Table 2.4) This changes are statistically significant at p-value = 0.007 and p-value = 0.107, respectively. After PAST, RAG appears as second agricultural LU that most reduces SCS_{30} by -57.7% when it was replaced in FOR areas and by -23.9% in CDO areas, with significance levels of p-value = 0.018 and p-value = 0.254, respectively. IRR reduces SCS_{30} by 12.2% when compared to FOR (p-value = 0.399), and increases by 11.8% (p-value = 0.332) in relation to CDO areas.

For most part of the natural LC replacement by agricultural LU, SCS_{30} decreased, even though that this decreasing was extremely likely or virtually certain for only two cases. The first case is when FOR is replaced by RAG (p-value = 0.018), and by PAST (p-value = 0.007) (Table 2.5). Between agricultural LUs, the use of IRR practice increases SCS_{30} by 41% when compared to RAG (p-value = 0.018), and 62.5% when compared to PAST (p-value = 0.007).

The patterns for SCS_{60} are similar to the ones found in SCS_{30}, with SCS_{60} decreasing the according to the order: FOR, IRR, CDO, RAG and PAST. The average of SCS_{60} values for FOR, IRR and CDO areas were 63.4 ± 33.2 Mg-C ha^{-1}, 61.2 ± 15.1 Mg-C ha^{-1} and 51.4 ± 29.2 Mg-C ha^{-1}, respectively (Table 2.3). For RAG and PAST, the SCS_{60} values were 42.6 ± 26.6 Mg-C ha^{-1} and 36.8 ± 15.1 Mg-C ha^{-1} (Table 2.3).

Considering the full soil profile (0-100 cm of depth), SCS_{100} estimates for FOR and CDO were 82.5 ± 43.6 Mg-C ha^{-1} and 70.3 ± 41.6 Mg-C ha^{-1}, respectively (Table 2.3). For the agricultural LUs, the SCS was 78.1 ± 25.5 Mg-C ha^{-1} for IRR, 57.4 ± 33.3 Mg-C ha^{-1} for RAG and 51.7 ± 25.5 Mg-C ha^{-1} for PAST. These results show that higher SCS_{100} losses may occur when FOR or CDO areas are replaced by PAST, reducing the SCS_{100} by -37.3% (p-value = 0.031) and by -26.4%, respectively (p-value = 0.155) (Tables 2.4 and 2.5). Here, RAG is the second agriculture LU that most reduces SCS_{100} by -30.3% (p-value = 0.053) when allocated in FOR areas and -18.2% (p-value = 0.269) when allocated in CDO areas. Lastly, IRR activities show a reduction of -5% (p-value = 0.704) in SCS_{100} compared to FOR, and an increase of 11.1 % (p-value = 0.455) compared to CDO areas (Tables 2.4 and 2.5). The SCS reduction when FOR is replaced by PAST (p-value = 0.031). The replacement of

PAST by IRR may increase the SCS_{100} in 51% (p-value = 0.022), while replacement of RAG by IRR may lead to an increase of 36% (p-value = 0.034) (Tables 2.4 and 2.5).

Table 2.3. Soil carbon stock in Mg-C ha^{-1} for 0-30 cm, 0-60 cm, 0-100 cm for different land use and land cover classes in Western Bahia

Depth		0-30 cm			0-60 cm			0-100 cm		
LUCCs	*n*	*avg*	*std*	*ci*	*avg*	*std*	*ci*	*avg*	*std*	*ci*
FOR	19	51.0	25.9	12.5	63.4	33.2	16.0	82.5	43.6	21.0
IRR	20	45.5	11.4	5.18	61.2	15.1	6.91	78.1	25.5	11.8
CDO	23	40.1	23.3	10.1	51.4	29.2	12.6	70.3	41.6	18.0
RAG	20	32.3	20.4	9.6	42.6	26.6	12.5	57.4	33.3	15.6
PAST	21	28.0	11.4	11.4	36.8	15.1	15.7	51.7	25.5	19.7

Averages (*avg*) followed by standard deviation (*std*) and confidence interval (*ci*) at $\alpha = 0.05$.

Table 2.4. Soil carbon stock changes between agriculture LU and native vegetation LC in Western Bahia for 0-30 cm and 0 100 cm of depth

Soil carbon stock Mg-C ha^{-1}			0-30 cm		0-100 cm	
			FOR	CDO	FOR	CDO
	0-30 cm	0-100 cm	51.0	40.1	82.5	70.3
IRR	45.5	78.1	-12.2%	11.8%	-5.34%	11.1%
RAG	32.3	57.4	-57.7%	-23.9%	-30.3%	-18.2%
PAST	28.0	51.7	-82.1%	-43.1%	-37.3%	-26.4%

Table 2.5. p-value obtained by Student's t-test to mean differences between agriculture LU and native vegetation LC in Western Bahia for 0-30 cm and 0-100 cm of depth

0-30 cm layer					
	FOR	IRR	CDO	RAG	PAST
FOR	-	0.399	0.164	0.018	0.007
IRR	0.399	-	0.332	0.018	0.007
CDO	0.164	0.332	-	0.254	0.107
RAG	0.018	0.018	0.254	-	0.547
PAST	0.007	0.007	0.107	0.547	-
0-100 cm layer					
	FOR	IRR	CDO	RAG	PAST
FOR	-	0.704	0.363	0.053	0.031
IRR	0.704	-	0.455	0.034	0.022
CDO	0.363	0.455	-	0.269	0.155
RAG	0.053	0.034	0.269	-	0.635
PAST	0.031	0.022	0.155	0.635	-

In summary, it is extremely likely that the replacement of Forest Formations by Pasture implies in a reduction of SCS_{100} by -37.3% (p-value = 0.031), and it is very likely that the replacement of Forest Formations by Rainfed Agriculture reduces SCS_{100} by -30.3% (p-value = 0.053). However, it is likely that conversion of savanna formations to Rainfed Agriculture or Pasture decreases SCS_{100} by -18.2% and -26.4% (p-value ≤ 0.333). It is more likely than not that the conversion of Cerrado Formations to Irrigated Agriculture reduces SCS_{100} (p-value ≤ 0.455), and increases the SCS_{100} of Cerrado areas, by 11.1%. For the conversion of Forest Formations to Irrigated Agriculture, it is unlikely that SCS_{100} decreases by -12.2%.

On the other hand, it is extremely likely that the conversion of Pasture (p-value = ≤ 0.022) or Rainfed Agriculture (p-value ≤ 0.034) to Irrigated Agriculture increases SCS_{100}.

2.3.2 Spatial and temporal patterns of carbon stocks for Western Bahia

This section presents the results of the historical reconstruction of carbon stocks. The spatial carbon stocks for AGB, BGB, SCS_{100} and total carbon stock are presented in Mg-C ha^{-1}. In order to compare the amount of carbon through the years, I use the sum of the three stocks for the entire region for each OBahia class and present these values in Tg-C (1 Tg-C = 10^6 Mg-C).

2.3.2.1 Regional patterns

The patterns of AGB, BGB and SCS_{100} for 1990, 1997, 2004, 2011 and 2018 are presented in Figure 2.4, Figure 2.5 and Figure 2.6, respectively. The AGB stocks decreased from 1990 to 2018, with west-east gradient (Figure 2.4a-e). In 1990, higher AGB values (> 15 Mg-C ha^{-1}) were concentrated in the extreme northwest, and in the north of Corrente basin, while AGB values in extreme west were predominantly below

1.5 Mg-C ha^{-1}. During 1997, 2004, 2011 and 2018, the AGB decreased mainly in the northeast region between the states of Piauí and Bahia, and in the east of the Corrente and the Carinhanha basins (Figure 2.4a-e).

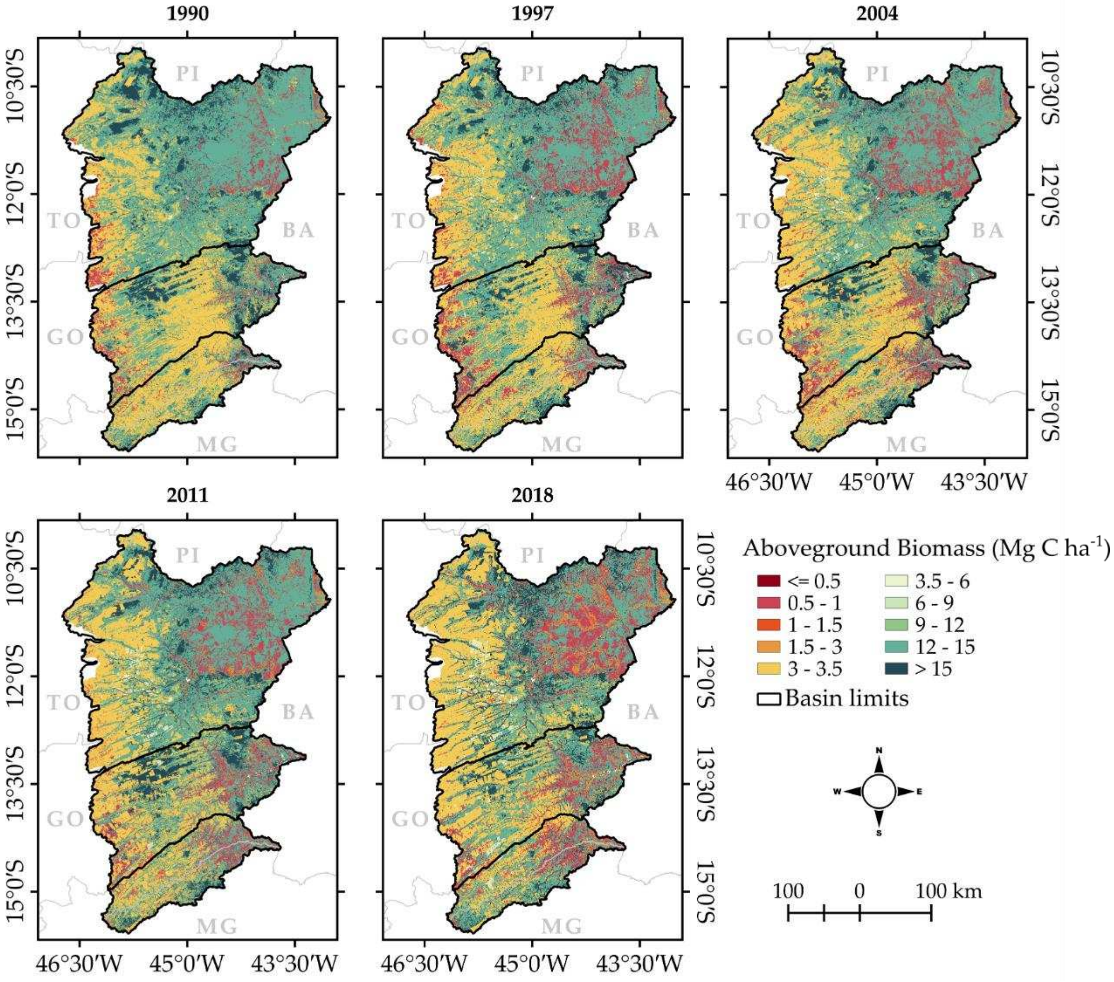


Figure 2.4. Aboveground biomass for Western Bahia in Mg-C ha^{-1} for (a) 1990, (b) 1997, (c) 2004, (d) 2011, and (e) 2018.

The BGB patterns are in agreement with AGB, decreasing gradually from 1990 to 2018, from west to east (Figure 2.5a-e). In 1990, the BGB values ranged between 1.5 and 3 Mg-C ha^{-1} in extreme west, due to a predominance of RAG_C, and $PAST_C$ in this region. In 1997, 2004, 2011, and 2018, it is possible to observe that there was a reduction of BGB with replacement areas from 3.5 and 9 Mg-C ha^{-1}, by areas ranging BGB from 1.5 to 3 Mg-C ha^{-1}.

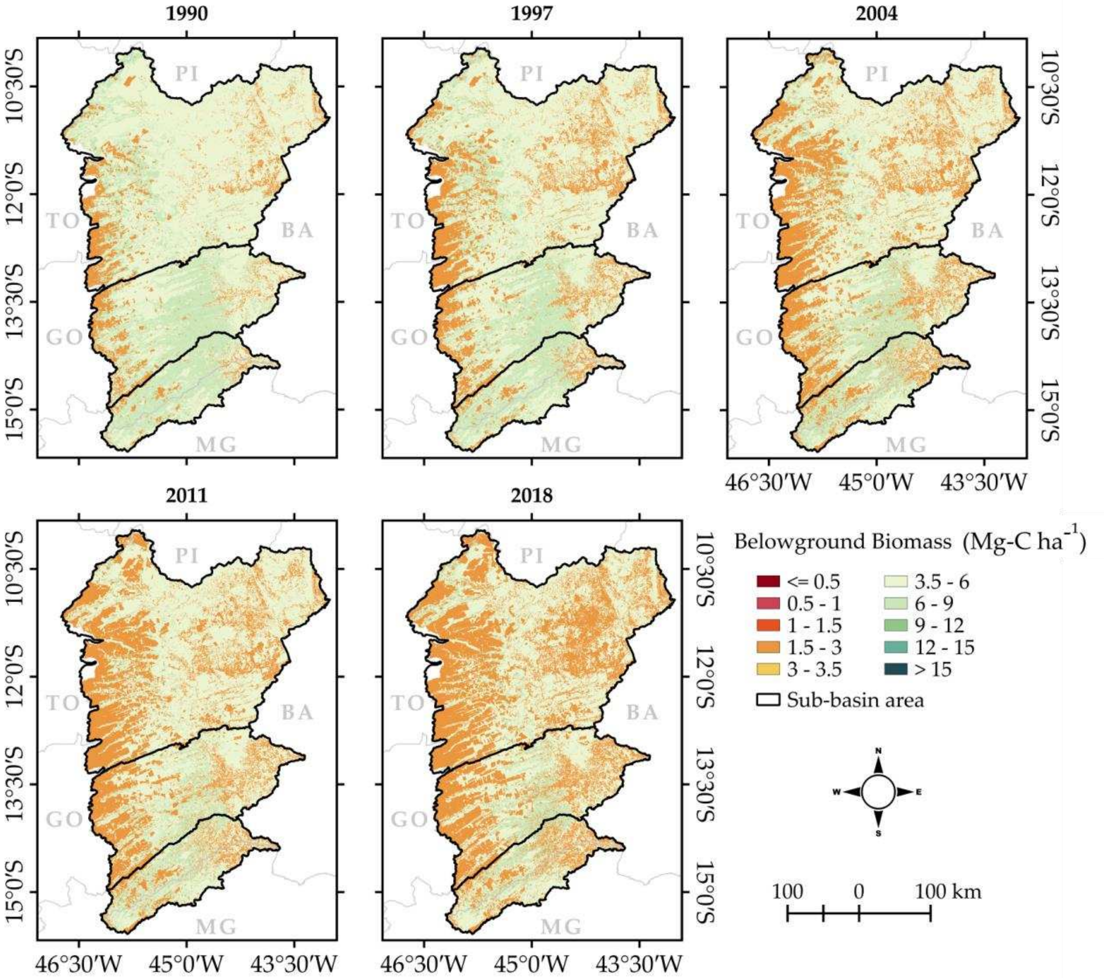


Figure 2.5. Belowground biomass for Western Bahia in Mg-C ha^{-1} for (a) 1990, (b) 1997, (c) 2004, (d) 2011, and (e) 2018.

The uncertainties of AGB and BGB estimates are mainly associated to the input data and to the use of homogeneous value for AGB and BGB to similar physiognomies, due to by the lack of observed data, as mentioned in the methodology. Thus, it is not possible to quantify the numeric uncertainty associated to AGB and BGB values.

The SCS$_{100}$ has also decreased through time (Figure 2.6a-e). For 1990, the Monte Carlo simulated SCS$_{100}$ ranged between 24.0 Mg-C ha^{-1} and 127.0 Mg-C ha^{-1} throughout the region and presented a larger variability compared to AGB and BGB patterns due to the previous knowledge of the variance of the observed data. Due to the spatial resolution (pixels with 30 m) it is difficult to observe SCS$_{100}$ gradient in the region, although it is directly associated with the spatial patterns of AGB and BGB.

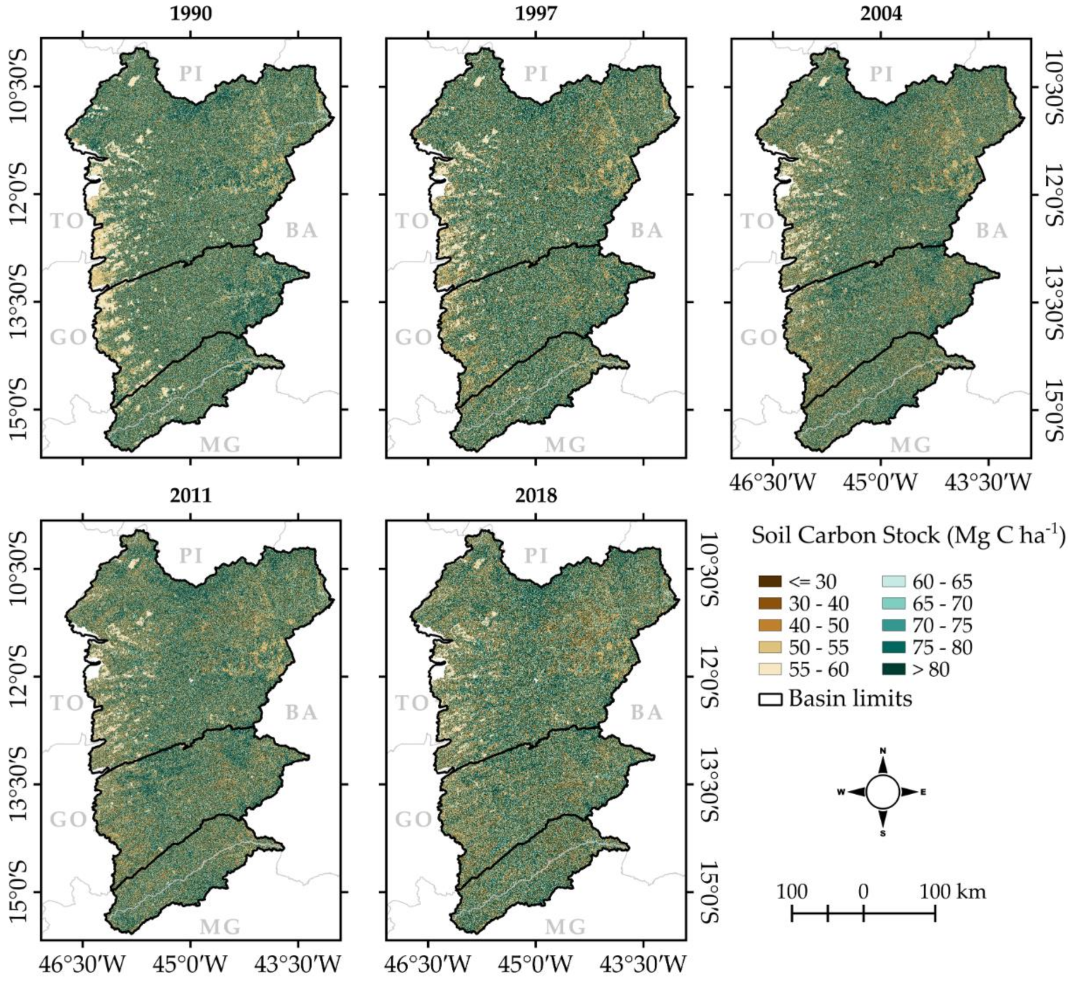


Figure 2.6. Soil Carbon Stock for Western Bahia Mg-C ha^{-1} for (a) 1990, (b) 1997, (c) 2004, (d) 2011, and (e) 2018.

The spatial patterns of carbon balance for 1997-1990, 2004-1997, 2018-2011 and, 2018-1990 for Western Bahia are shown in the Figure 2.7. It is possible to observe that there are a wide carbon losses between 1997-1990 and 2018-1990 (Figure 2.7a and Figure 2.7e). Between 2018 and 1990, the carbon losses are observed in the northwest of Western Bahia, between TO-PI and in northeast of BA-PI borders, with reduction of -30 Mg-C ha^{-1} (Figure 2.7e). These reductions are also observed in the Southeast and through the north-south border of Western Bahia (Figure .7e), while a slight increase of total carbon stocks is observed in the central part of Western Bahia (Figure 2.7e). The higher losses between BA-TO, and BA-MG can be influenced by the climate, which in these areas is more seasonal than in the extreme west where it is Aw predominant. The lower annual rainfall amount rainffal associated to high dry season length contributes to a decrease in both organic matter acumulation and increase of decomposition rates of the litter, leading to higher carbon losses.

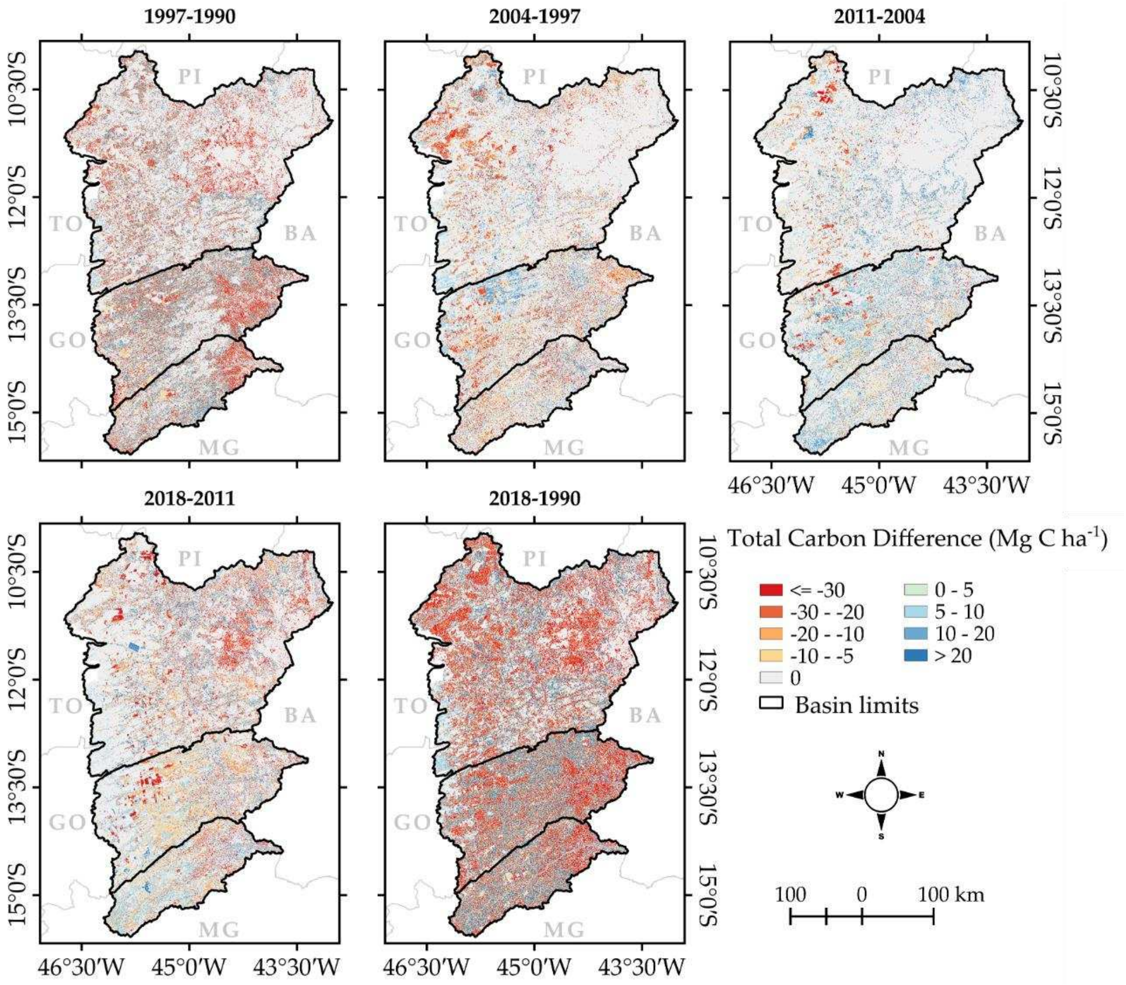


Figure 2.7. Total carbon difference for Western Bahia in Mg-C ha^{-1} for (a) 1997 - 1990 (b) 2004 - 1997, (c) 2011 - 2004, (d) 2018 - 2011 and (e) 2018 - 1990.

2.3.2.2 Regional balance

Regional carbon balance was calculated from the totals of AGB, BGB and SCS_{100}. In Table 2.6, I present the values of SCS_{100} for all agricultural LU and native LC classes for 1990, 1997, 2004, 2011, and 2018.The SCS_{100} in 1990 was 92.5 ± 24.1 Tg-C, distributed in 55.0 ± 14.3 Tg-C for the Grande Basin, 24.9 ± 6.42 Tg-C for the Corrente, and 12.6 ± 3.38 Tg-C for the Carinhanha Basin (Table 2.6 and Table C1). For 1990 in Western Bahia, native vegetation areas represented a SCS_{100} of 83.2 ± 24.1 Tg-C, while agriculture land uses (RAG_C + $PAST_C$ + $RAG/PAST_C$) showed stocks of 9.16 Tg-C and the IRR_C stock of 0.138 Tg-C. These values show there were 90% of SCS_{100} in native vegetation cover, 9.90% stocked in the RAG_C + $PAST_C$ + $RAG/PAST_C$, and only 0.15% in Irrigated Agriculture in 1990.

In 2018, the amount of SCS100 totalized 87.3 ± 25.0 Tg-C, from which 55.1 ± 15.1 Tg-C corresponds to natural vegetation areas (FF, SF and GF), 30.7 ± 9.63 Tg-C by RAG_C + $PAST_C$ + $RAG/PAST_C$ areas, and 1.54 Tg-C by IRR_C areas (Table 2.6). The amount of SCS_{100} is distributed according to: 63.1% in native vegetation cover, 24.1% stocked in the RAG_C + $PAST_C$ + $RAG/PAST_C$, and 1.76% in irrigated areas. The difference between 1990 and 2018 shows that the amount of SCS_{100} in native vegetation (FF + SF + GF) decreased from 90% to 63.1%, while RAG_C + $PAST_C$ + $RAG/PAST_C$ increases from 9.90% to 24.1%, and IRR_C increases from 0.15% to 1.76%. However, the increase of SCS_{100} in +13.32 Tg C in 2018, was not enough to compensate carbon losses by natural areas (-28.15 Tg C).

Table 2.6. Soil carbon stocks in Western Bahia for all land use and land cover classes

LULCCs for Western Bahia	1990		1997		2004		2011		2018	
	avg	std	avg	std	avg	std	avg	std	avg	std
	Tg-C									
FF	12.1 ±	3.60	11.1 ±	3.12	10.9 ±	2.84	14.7	± 3.74	14.8 ±	3.73
FS	45.8 ±	13.3	42.9 ±	12.3	39.4 ±	11.3	40.3	± 11.5	32.5 ±	9.21
FG	25.3 ±	7.23	20.5 ±	5.79	16.7 ±	4.68	8.85	± 2.47	7.73 ±	2.16
RAG/PAST$_C$	0.438 ±	0.00	0.426 ±	0.074	0.476 ±	0.086	1.457	±0.270	3.52 ±	0.656
RAG$_C$	4.42 ±	0.00	6.93 ±	1.56	12.0 ±	3.19	15.3	± 4.23	17.7 ±	4.98
IRR$_C$	0.138 ±	0.00	0.463 ±	0.066	0.650 ±	0.099	0.843	±0.132	1.54 ±	0.248
PAST$_C$	4.30 ±	0.00	7.72 ±	2.64	8.57 ±	3.32	7.63	± 2.98	9.48 ±	3.99
Total	92.51 ±	24.12	90.14 ±	25.54	88.73 ±	25.48	89.13	±25.33	87.31 ±	24.97

The pattern of SCS$_{100}$ is also observed in ABG and BGB storages. In 1990 the amount of carbon stocked in AGB was 12.5 Tg-C. From 1990 to 2018, AGB decreased 14.5%, corresponding to a total loss of 1.8 Tg-C (Table 2.7). The BGB decreased -24.0% between 1990 and 2018, reducing the BGB storage from 6.91 Tg-C to 5.26 Tg-C in 2018 (Table 2.7). Although AGB and BGB show a decrease in carbon stocks between 1990 and 2018, these losses are smaller in magnitude than losses by SCS$_{100}$.

Table 2.7. Total of ABG, BGB and SCS in Western Bahia (Tg-C), and percentual changes for 1997, 2004, 2011 and 2018 compared 1990

	1990		**1997**		**2004**		**2011**		**2018**	
Western Bahia	*avg*	*std*	*avg*	*std*	*avg*	*std*	*avg*	*std*	*avg*	*std*
AGB	12.5	-	11.6	-	11.0	-	11.8	-	10.7	-
BGB	6.91	-	6.47	-	6.02	-	5.67	-	5.26	-
SCS	92.5	± 24.1	90.1	± 25.5	88.7	± 25.5	89.1	± 25.5	87.3	± 25.0
TCS	112	± 24.1	108	± 25.5	106	± 25.5	107	± 25.5	103	± 25.0
	%									
AGB	100%		-7.0%		-12.0%		-5.5%		-14.5%	
BGB	100%		-6.4%		-12.8%		-18.0%		-24.0%	
SCS	100%		-2.56%		-4.09%		-3.66%		-5.63%	
TCS	100%		-3.29%		-5.51%		-4.75%		-7.74%	

It is evident that TCS reduction is directly related to carbon losses by natural areas removing (FF, SF and GF) and an increase of agricultural areas through 1990 and 2018

(Figure 2.8). The TCS in 1990 was 112 ± 24.1 Tg-C, decreasing to 108 ± 25.5 Tg-C in 1995, 106 ± 25.5 Tg-C in 2004 and reaching 103 ± 25.0 Tg-C in 2018 (Table 2.7). Although both AGB and BGB contribute, respectively, in 14.5% and 24.0% of carbon amount reduction, the highest loss was from soils that presented a reservoir seven times greater than AGB, and twelve times greater than BGB (Table 2.7).

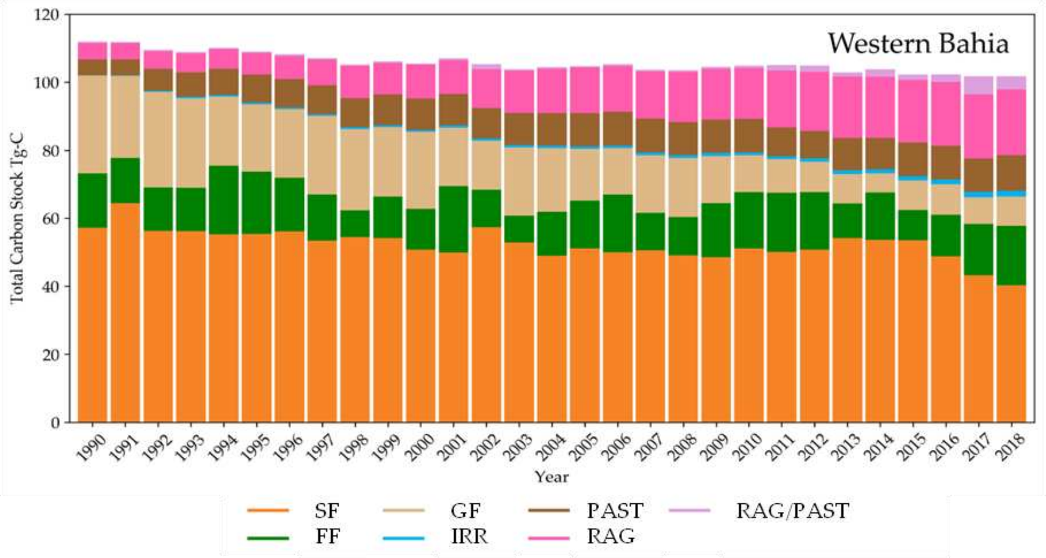


Figure 2.8. Temporal total carbon stock variability for different LULCC for Western Bahia region for the1990-2018 period.

2.4. Discussion

2.4.1 Soil Carbon stocks

The results presented in this study are in agreement with other studies in the Cerrado biome, which showed that land use affects the amount of total soil carbon stocks (Rosa et al., 2003; Ferreira et al., 2007; Leite et al., 2010). For natural areas in Western Bahia, such as CDO and FOR, soils stock an average of 51.4 ± 29.2 Mg-C ha^{-1} (average followed by standard deviation) and 63.4 ± 33.2 Mg-C ha^{-1} for 0-60 cm of depth, respectively, of which 40.1 ± 23.3 Mg-C ha^{-1} and 51.0 ± 25.9 Mg-C ha^{-1} are allocated in the 0-30 cm layer.

These values are lower than the ones reported by Wantzel et al. (2012) who estimated 60 ± 12.17 Mg-C ha^{-1} for 0-30 cm layer, and 97.2 ± 28.9 Mg-C ha^{-1} 0-60 cm layer for Cerrado native vegetation areas under sandy soils. On the other hand, Tivet et al. (2011) reported an average of 63.52 ± 3.45 Mg-C ha^{-1} for an Arenosols in Western Bahia at Luis Eduardo Magalhães for a CDO area. Differences on methodology, texture, climate, or other biophysics factors, may be responsible for differences between SCS estimates under natural vegetation covers. Tivet et al. (2011) for example, reported a difference of 2.5 Mg-C ha^{-1} between Walkey-Black and dry combustion methods used to estimate soil carbon stocks in Arenosols. The degree of preservation of Cerrado native areas is other fact that influences on the amount of SCS allocated at soil surfaces, affecting the organic matter accumulation and consequently the total soil carbon stock.

My results showed that FOR and CDO replacement by PAST or RAG decreases the SCS. However, pasture implementation, specially by *Brachiaria* pastures, is an activity that is considered by some studies that an alternative to increase the accumulation of carbon in Cerrado biome due to the higher net primary production, the potential for soil temperature reduction, and soil structure maintenance (Lal et al., 1998; Chapuis Lardy et al., 2002; Silva et al., 2004; Jantalia et al., 2007). For Western Bahia, PAST areas have been a higher source of carbon compared to RAG or IRR land uses. My estimates for 0-30 cm for PAST (28.0 Mg-C ha^{-1} ± 11.4 Mg-C ha^{-1}) is similar that founded by Wantzel et al. (2012) in sandy soils that estimated 28.87 Mg-C ha^{-1} ± 9.23 Mg-C ha^{-1} for a management Pasture, and lower when compared to degraded pasture areas (23.87 Mg-C ha^{-1} ± 5.67 Mg-C ha^{-1}). Compared to clay soils, the amount of carbon at 0-30 cm in Western Bahia is lower than estimated by Marchão et al. (2009) and Freitas et al. (2000), who found 45 Mg-C ha^{-1} and 45.5 Mg-C ha^{-1} for the 0-20 cm layer, respectively. The lower amount of SCS in PAST areas can be a result of losses by overgrazing, lack of annual maintenance of fertilization (liming, nitrogen, and phosphorus), or a lack of adequate management (presence of termite mounds and erosion process). Acid and low fertility of sandy soils of Cerrado, quickly decrease the amount of grass AGB in soils under grazing, and in case of no maintenance fertilization, a lower soil carbon stock is accumulated, leading to soil degradation. Different from Rainfed Agriculture, Pasturelands are not reformed each 4 years, but rather, the contrary, the extensive Pasturelands provide a broad space to re-grow grasses, and many farmers use them to until the complete Pasture depletion.

It is very likely that Forest Formations replacement by Rainfed Agriculture decreases the soil carbon stocks (30%, p-value = 0.053), while it is likely that Cerrado formations replacement by Rainfed Agriculture decreases soil carbon stocks in (18.2%, p-value = 0.269). These losses were expected due the reduction of plant roots and litter that returned to the soil, to the lower water retention capacity and to the low clay content in Cerrado sandy soils. Soil carbon stock losses estimated in this work for Rainfed Agriculture were higher than the losses reported by Ferreira et al. (2007), who found less 14% of soil carbon stock in areas under conventional tillage (CT) and less 6.3% for areas under no-tillage (NT) management.

Moreover, the results presented here suggest that Irrigated Agriculture could positively affects the carbon dynamics in Cerrado. It is likely that in 0-30 cm soil layer, soil carbon stocks are increasing in 11.8% in irrigated areas, while it is more likely than not that soil carbon stocks increases 11.1% in 0-100 cm layer. Moreover, it is extremely likely that Irrigated Agriculture increases in 28% the soil carbon stocks in 0-30 cm when compared to Rainfed Agriculture, and it is likely that it increases only 26.4% for 0-100 cm layer. Comparatively, the increase of soil carbon stocks in irrigated areas in relation to rainfed areas are in agreement with found by Rosa et al. (2003) which showed that soil carbon stocks increase by 37.8% in irrigated areas. The higher amount of carbon stocks may be related to the fact that irrigated samples were collected in the middle of crop cycle with at least two months without soil management, and with crop covering the soil surface. Moreover, the water availability constant associated to the land cover can be decrease the soil temperature favoring the process of organic matter decomposition. Although Irrigated Agriculture show a potential carbon dioxide removal activity by increasing soil carbon stocks in Western Bahia, the use of irrigation to remove carbon from atmosphere should be carefully evaluated, since this activity strongly relies on the availability of water resources and it is associate to a higher uncertainty level.

This study differs from others found in the literature since it estimates the carbon stock considering 0-100 cm depth and classify these stocks for different LULCCs. The low number of significant differences found among the soil carbon stocks for land use and land cover classes may be directly associated with a need for a larger number of samples, with a need of sub-samples usage, or a lack of knowledge regarding the long-term land use soil. In literature, it is possible to find studies that controlled the soil management historic, which points out that no-tillage practices and Pasture implementations may increase soil carbon stock. Leite et al. (2010), for example, found increases of 34%, 47%, and 61%, when no-tillage was applied during two, four and six ages for 0-40 cm layer, respectively. According to Corbeels (2016), a change of 8 million ha of cropland from conventional to no-tillage would represent a soil storage nearly 8 Tg-C yr^{-1} for 10 to 15 years in Cerrado domain.

In Western Bahia, the Rainfed Agriculture is the predominant land use stocking an average of 33.3 ± 15.6 Tg-C under soils, and could represent a potential space for implementation of CDR practices to increase soil carbon stocks and decrease carbon emissions. In the region, farmers use mixed tillage to avoid annual soil revolving and to reduce carbon losses. However, there are no studies that quantify how much carbon a mixed tillage practice is able to stock over time in sandy soils of Cerrado, and it is a knowledge extremely relevant once the most dynamic agriculture frontier is located under these soils.

In the present study, random sample collection separated only by land use and land cover classes demonstrated that areas of Rainfed Agriculture and Pasture seem to be acting as a source of carbon to the atmosphere, while Irrigated Agriculture practice may be a potential alternative for mitigation of emissions. My results show that the adoption of Irrigated Agriculture practices can remove carbon from the atmosphere but not in enough quantity to compensate emissions due to deforestation, which reinforces that no deforestation is still the best alternative to reduce carbon emissions. However, as previously discussed, it is necessary to increase the reliability of these estimates in order to elaborate and suggest management practices with a higher chance of effectively mitigate carbon emissions in Western Bahia. Although Western Bahia are partially located under Urucuia aquifer and it is drained by three important basins, the water availability may be a limiting factor to irrigation, if not managed with responsibly. The amount of grants for water use is directly linked to the streamflow of rivers, which depends on the precipitation rates, duration of wet season, and the maintenance of natural vegetation cover and by recharge rates of the aquifer. In Chapter 1, the presented results showed that even though agriculture land uses do increase soil compaction and reduce soil porosity, they do not significantly affect the vertical flow of water in the soil. However, the replacement of wide vegetation areas by agricultural activities could decrease one of the main ecosystem services of vegetation, the formation of precipitation.

2.4.2 Spatial and Temporal patterns of carbon stocks for Western Bahia

The extreme dynamics of land use change (Sano et al., 2000; Oliveira et al., 2017) and occupancy processes (Branstronn et al., 2009; Oliveira et al., 2017) in Western Bahia make this region strategic for carbon dynamics studies. The historical reconstruction of carbons stocks developed in this study, allowed determination of the Western Bahia role in the gain and loss of carbon throughout 1990 and 2018 period. Along this period, Western Bahia emitted about 7 Tg-C being characterized as a source of carbon to the atmosphere.

Spatial patterns of total carbon stocks are in agreement with the dynamics of Western Bahia occupation (Branstronn et al., 2009; Oliveira et al., 2017). The total carbon stock decreases in the central west portion and progresses to the eastern region, and expands toward the north and south limits. This result is associated to patterns present in land use and land cover database used for carbon historical reconstruction. The errors associated to the random forest classifier in OBahia, affects the regional carbon balance calculated by bookkeeping model. The change of grasses areas to forest areas between two years, or forest areas to water is some of the problems that will be solved in the next version of the OBahia database.

The expansion of agricultural land uses on the region is responsible for increasing the amount of total carbon stocks in the land use classes, but it is not sufficient to change the carbon balance to positive. The negative carbon balance for the Western Bahia obtained in this study reinforces that soils are the key role to offset or reduces the carbon emissions in the region once this reservoir is responsible an average of 83% of total carbon stocked in the region. And show that an increase of 12% of soil carbon stocks is able to offset the carbon losses.

The spatial patters of carbon balance is an important tool to identify priorities and potential areas to implement of carbon dioxide removal and carbon mitigation practices. In Western Bahia, different practices to reduce carbon emission may be recommended. Based on maps elaborated in this thesis, two possible strategic areas could be in the Formosa do Rio Preto region (between TO-PI), and in the middle of Angical region (11°S, 44.5°W, Figure 2.7) which showed high trend losses over the 27 years. These areas present different landscapes and land uses predominance. In Formosa, there is predominance of flat areas under Rainfed Agriculture, where the soybean is the main cropping tillage, while in the Angical, there are seasonal forest predominance used for Pasture areas.

Recognizing areas with the highest and lowest carbon loss rates is a step forward to identify priority areas for carbon emission reduction. Thus, this study contributes to the first spatial and temporal patterns of carbon in the most dynamic agriculture frontier in Brazil. Although the limitations as no considered the rates of re-growing vegetation, management type it provides a holistic vision about the trends of total carbon stocks in Western Bahia, favoring the identification areas and activities that can contribute to development of sustainable agriculture.

2.5. Conclusion

The main conclusions of this chapter are:

- It is extremely likely that the replacement of Forest Formations by Pasture implies in a reduction of SCS_{100} by-37.3% (p-value = 0.031), and it is very likely that the replacement of Forest Formations by Rainfed Agriculture reduces SCS_{100} by -30.3% (p-value = 0.053).
- It is likely that conversion of savanna formations to Rainfed Agriculture or Pasture decreases SCS_{100} by -18.2% and -26.4% (p-value ≤ 0.333).

- It is more likely than not that the conversion of Cerrado Formations to Irrigated Agriculture reduces SCS_{100} (p-value ≤ 0.455), and increases the SCS_{100} of Cerrado areas, by 11.1%.
- For the conversion of Forest Formations to Irrigated Agriculture, it is unlikely that SCS_{100} decreases.
- It is extremely likely that the conversion of Pasture (p-value ≤ 0.022) or Rainfed Agriculture (p-value ≤ 0.034) to Irrigated Agriculture increases $SCS_{100.}$
- Historically, Western Bahia lost 6.25% of the total carbon stock, with a decrease from 112 Tg-C in 1990 to 103 Tg-C in 2018.

Despite the limitations and uncertainties associated with the results presented in this thesis, it is possible to conclude that the impacts of land use change are a reality at the agricultural frontier of the Cerrado and there is an urgent need to monitor how these changes occur over time. A temporal monitoring study of these effects is crucial to identify management practices and the time scale needed to change the carbon loss trend, contributing to the development of effective gas emission mitigation strategies for the sandy soil domain of Cerrado agriculture frontier. It is a relevant conclusion because although my results shows that it is extremely likely that Irrigated areas present higher soil carbon stocks compared natural areas, it is not possible to determine the resilience of stored carbon. If the soil carbon stock in these areas has associated with a short time period, this management practice would not qualify as a carbon dioxide removal (CDR). Moreover, the water availability is as a limiting factor. The irrigation, if not managed with responsibly, can affects the streamflow of rivers, the precipitation rates and the recharge rates of the Urucuia aquifer. Currently, seven regions in Western Bahia have been identified where the potential for water use conflicts is critical (Pousa et al., 2019), which demonstrate that increases the irrigation areas is not better way to reduce carbon losses.

There is an urgent need to develop a monitoring system able to show the availability and demand of water resources and the behavior of soil carbon stocks in a long-term.

If on one hand, the analyzed data in this chapter show that Western Bahia has been a carbon source to the atmosphere, and it is contributing to increase the global warming and climate change, on the other hand, it was possible to identify priority areas (with greater amount of carbon loss) and encourage the adoption of more sustainable agricultural practices, in particular soil management practices.

Increase and maintenance of soil carbon stocks are a big challenge for regions, where soils are naturally acidic and the seasonal climate presents irregularities in the precipitation distribution. During the fieldwork, it was observed that some farmers have been looking for alternatives to solve this challenge, using a wide crop rotation system, a mixed planting system, or using high technology to avoid soil compaction. However, as my results demonstrate, the challenge remains.

CHAPTER 3. GENERAL CONCLUSIONS AND REMARKS

The development of public policies for food security and climate change mitigation relies mainly on studies that quantify the sources and sinks of carbon on the environment and evaluate the agriculture sustainability of land uses. The present study is the first to provide databases for physic and hydraulic soil properties and descriptive carbon content for a sandy soil domain of a Cerrado agriculture frontier, which is considered the largest and most active agricultural frontier in Brazil, the Western Bahia.

The databases developed in this thesis will be used by model simulations and to assessment of territorial intelligence. The soil physical database is currently used to calibrate the Brazilian land surface model – INLAND, developed by the Research Group on Atmosphere-Biosphere Interaction and by the National Institute for Space Research INPE, to obtain the spatial and temporal patterns of water table recharges considering the influence of land use change. The recharge patterns and the estimates of carbon stocks will be used to guide assessment of territorial intelligence to identify priority areas for implementation of carbon dioxide removal practices and potential areas for natural ecosystem preservation.

The estimates of soil carbon stocks in this study showed that the sandy soil of Western Bahia presents lower soil carbon stocks compared to the clay soils of Brazilian Central West, and that there are wide differences between land use and land cover classes on the region. The largest amount of soil carbon was found in Irrigated areas, followed by Forest Formations, Cerrado Formations, Rainfed Agriculture and Pasture for 0-100 cm. However, it is not possible to affirm that that soils in irrigated areas store more carbon than natural vegetation areas. For this, it is necessary evaluate the resilience of stored carbon and monitoring the soils in long-term. The agricultural soils suffer annual management interferences, whether for planting or fertility correction which may reduce soil carbon resilience, leading to annual soil carbon losses. Although the results show that irrigation may be a potential tool to increase soil carbon stock, careful analysis should be performed to assess the resilience of carbon stocks in these sandy soils and the impact of increased irrigation in Western Bahia. If the soil carbon stock in Irrigated areas is associated with a short residence time, this management practice would not qualify as a carbon dioxide removal (CDR).

Regionally, this thesis showed that over the last 28 years Western Bahia has presented a decreasing trend of total carbon stocks, and that the agricultural land uses as Rainfed Agriculture and Pasture did not increase the amount of soil carbon stocks, especially when replace Forest Formations areas. However, the historical carbon losses should be interpreted carefully, since this conclusion is based only on losses caused by the difference between the average stocks of each land use, not considering annual losses from fires, and annual carbon increments from conservation practices such as no-tillage and the implementation of crop-livestock integration.

Future research efforts should focus on long-term estimate of the carbon sinks in agricultural land-uses considering different management types. A long-term monitoring study of these land uses would provide information on the individual behavior of the carbon accumulation curve for each type of management and would allow parameters derivation for use in dynamic soil and vegetation spatial modeling.

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APPENDIXES

APPENDIX A

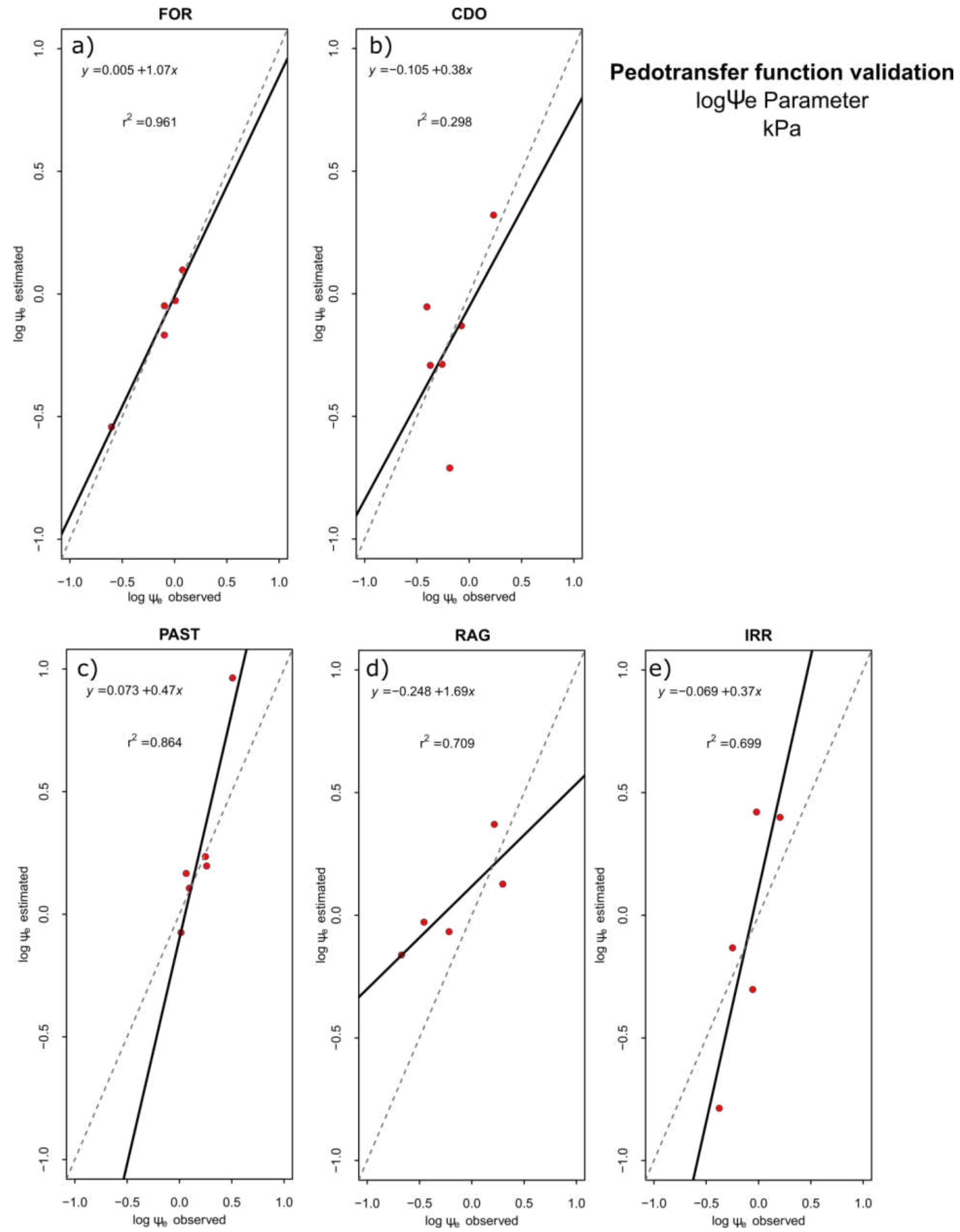

Figure A1.Correlation between ψ_e observed and log ψ_e estimated by Pedotransfer functions in the Table 1.2 for Cerrado formations (CDO), Forest formations (FOR), Rainfed Agriculture (RAG), Irrigated Agriculture (IRR), and Pasture (PAST).

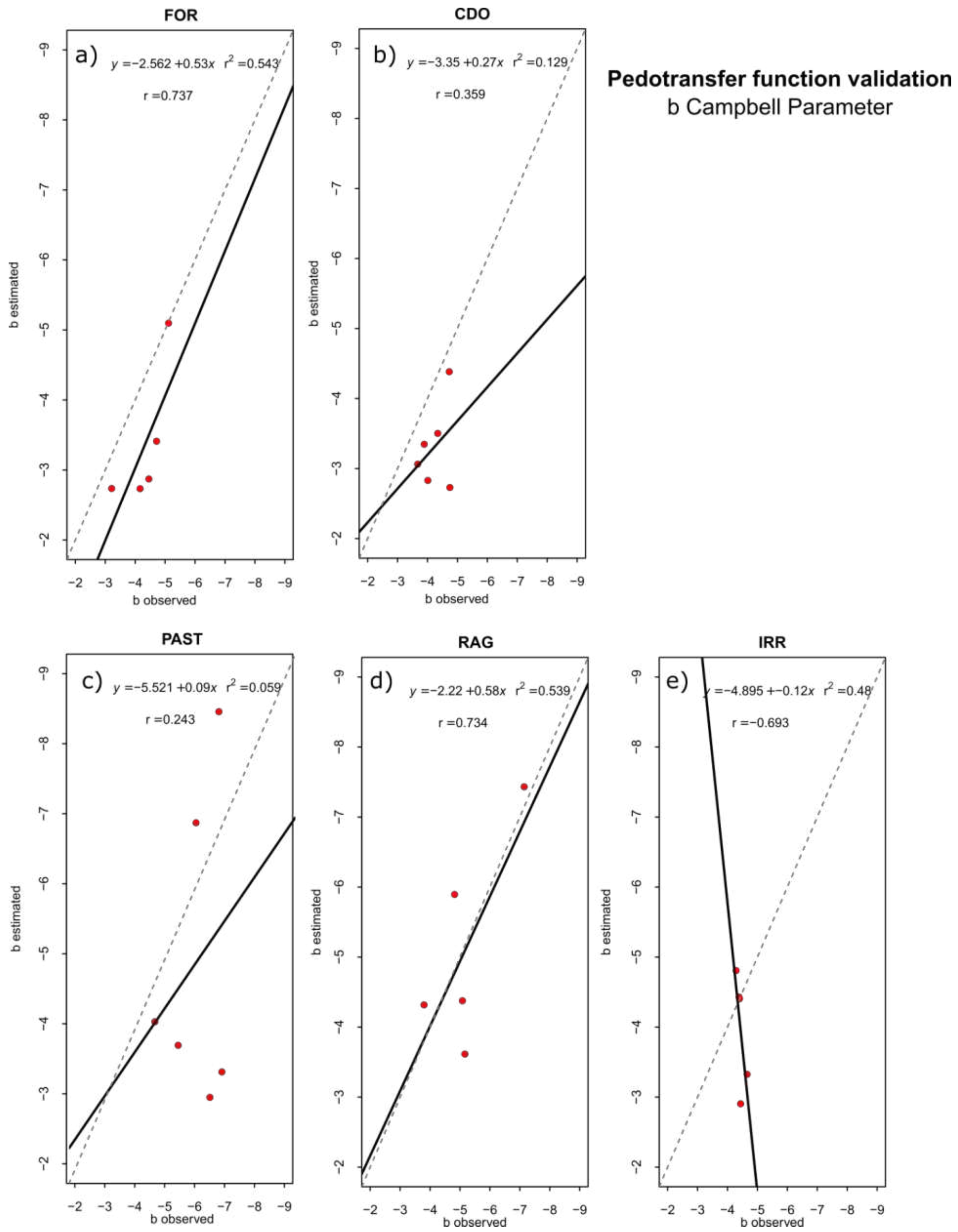

Figure A2.Correlation between b Campbell observed and estimated by Pedotransfer functions in the Table 1.2 for Cerrado formations (CDO), Forest formations (FOR), Rainfed Agriculture (RAG), Irrigated Agriculture (IRR), and Pasture (PAST).

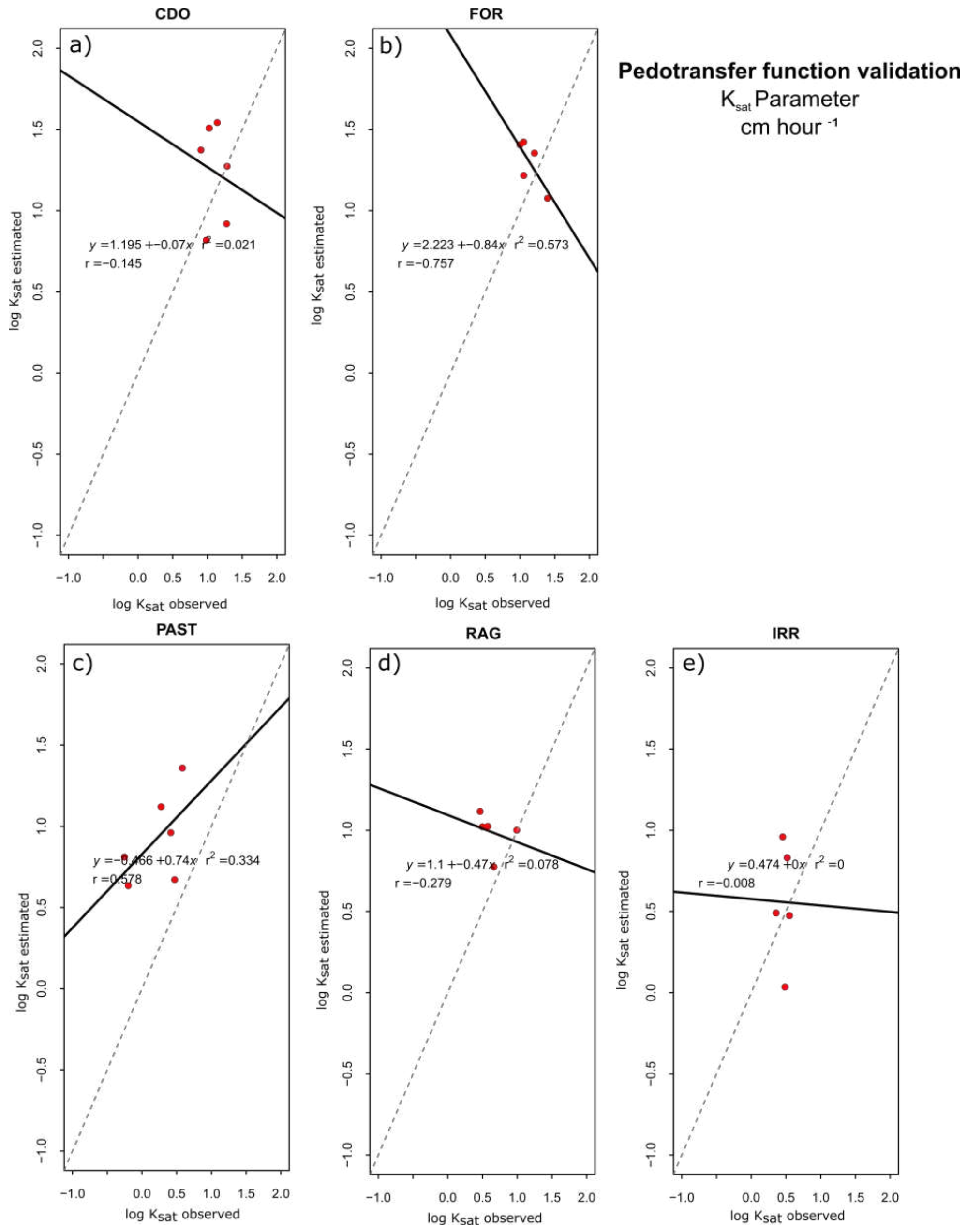

Figure A3. Correlation between K_{sat} observed and K_{sat} estimated hydraulic by Pedotransfer functions in the Table 1.2 for Cerrado formations (CDO), Forest formations (FOR), Rainfed Agriculture (RAG), Irrigated Agriculture (IRR), and Pasture (PAST).

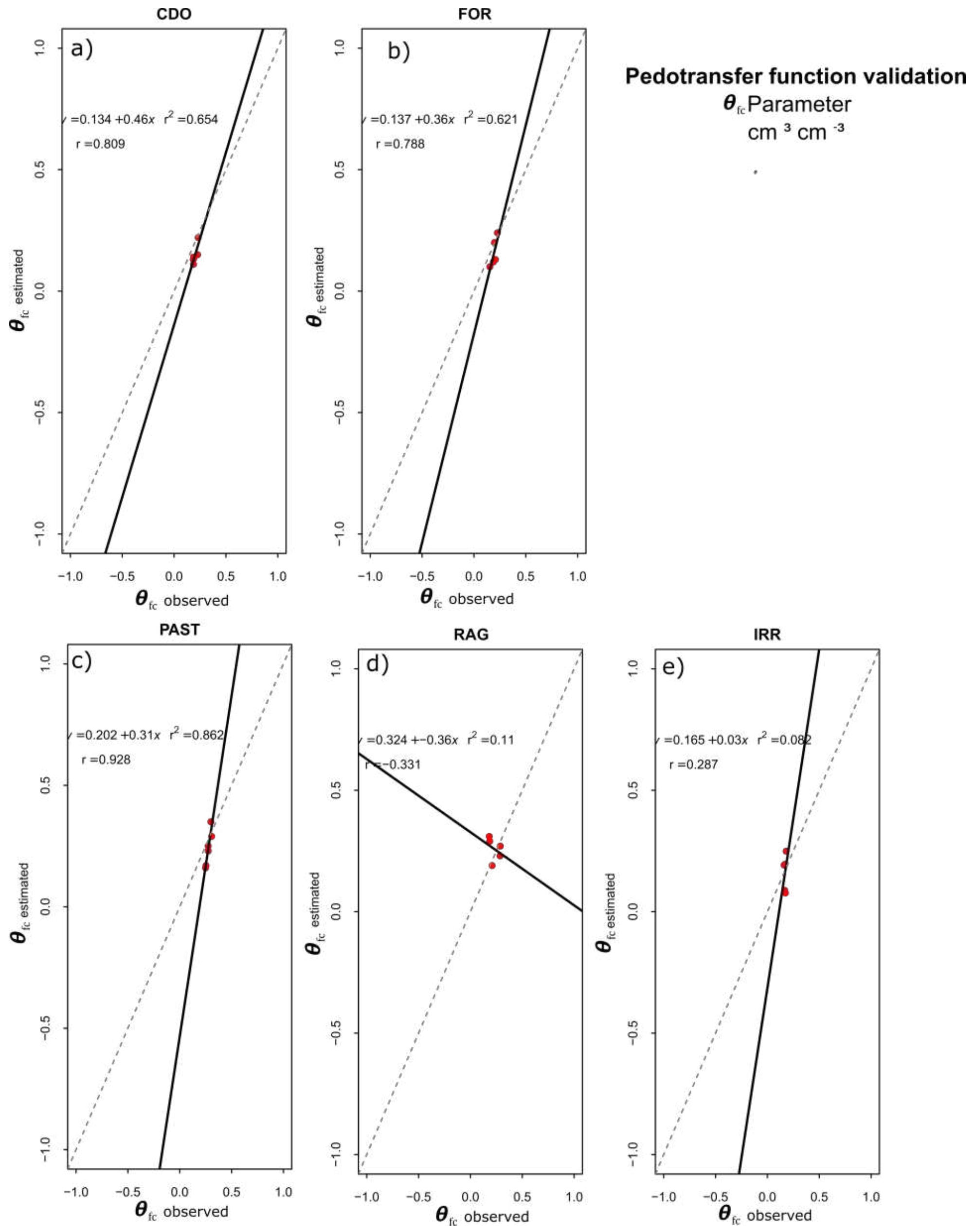

Figure A4.Correlation between θfc observed and θfc estimated by Pedotransfer functions in the Table 1.2 for Cerrado formations (CDO), Forest formations (FOR), Rainfed Agriculture (RAG), Irrigated Agriculture (IRR), and Pasture (PAST).

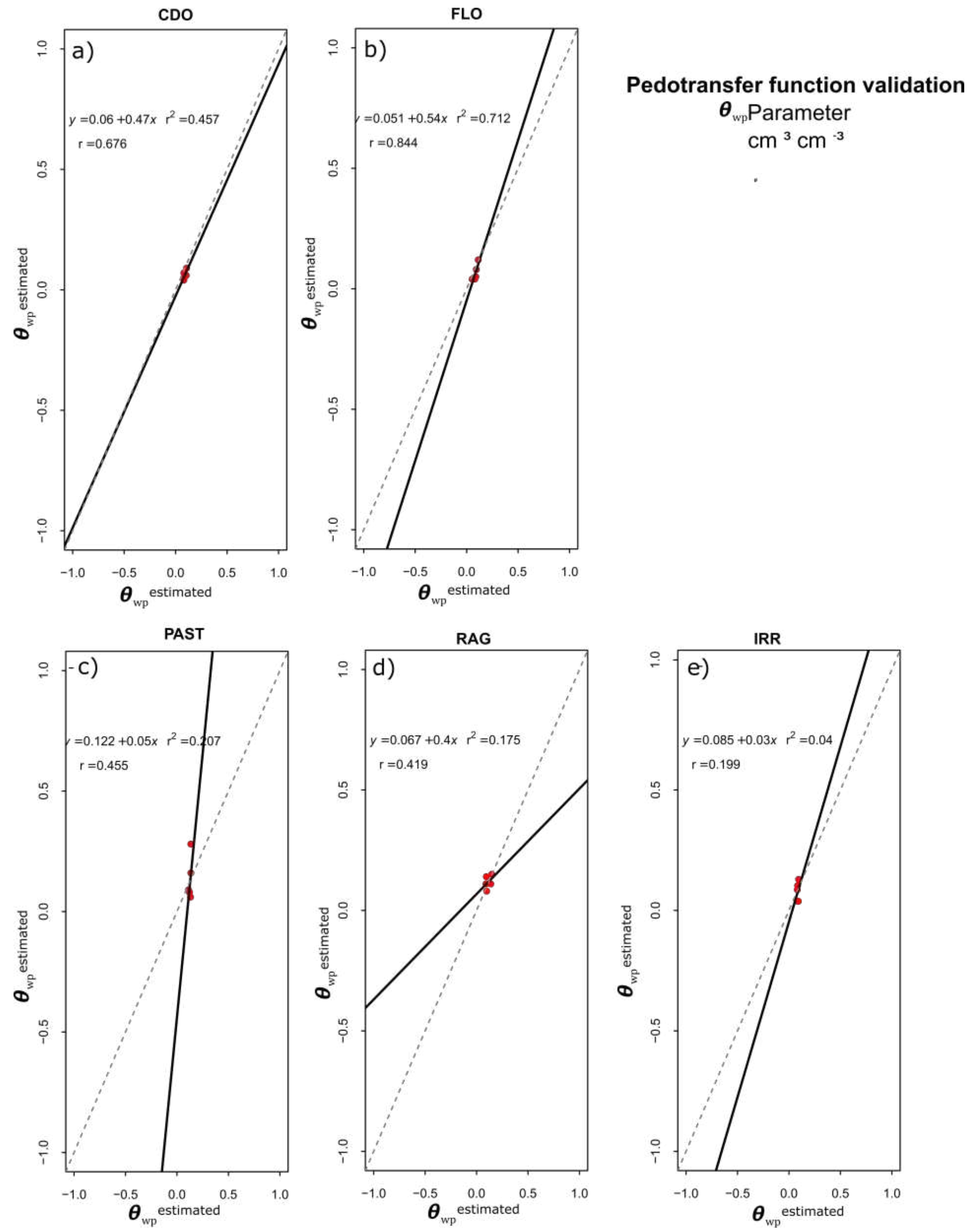

Figure A5.Correlation between θwp observed and θwp estimated by Pedotransfer functions in the Table 1.2 for Cerrado formations (CDO), Forest formations (FOR), Rainfed Agriculture (RAG), Irrigated Agriculture (IRR), and Pasture (PAST).

APPENDIX B

The AGB values were obtained from Avitabile et al. (2016) for Seasonal Forest, from Lima Júnior et al. (2014) for Caatinga arbustiva and from Castro and Kauffman (1998) for Campo Limpo. For vegetation physiognomies as Galeria Forest (Veredas), Campo Sujo and Cerradão the AGB data were obtained from Santana et al., (2013), and for typical Cerrado was obtained from Teodoro (2014) (Table B1). The all BGB data were obtained from Third Edition of the Annual Estimates of Greenhouses Gas Emissions Report (2015). The AGB and BGB values (Mg ha^{-1}) were transformed to carbon stocks (Mg-C ha^{-1}) using the ratio of 0.485 as proposed by Leite et al. (2011).

Table B1. Land covers from INEMA and RADAMBRASIL classification used to development of spatial native vegetation map according to Forest Formations – FF, Savanna Formations – SF and Grasses Formations – GF. The AboveGround (AGB) and BelowGround (BGB) biomass used these reference values to development of spatial native vegetation AGB and BGB stocks in the 1990. All BGB data from Bustamante et al., (2015).The sources are RS- Remote Sensing, and FI- Forest Inventory

Classes according to INEMA and RADAMBRASIL classification	OBahia classes	AGB Mg ha^{-1}	Reference	Source of data	BGB Mg ha^{-1}
Floresta Estacional	FF	40.5	Avitabile et al., (2016)	RS	12.4
Veredas	FF	25.3	Santana et al., (2013)	FI	7.28
Floresta Estacional Decídua Montana	FF	40.5	Avitabile et al., (2016)	RS	12.4
Floresta Estacional Decídua Submontana	FF	40.5	Avitabile et al., (2016)	RS	12.4
Floresta Estacional Semidecidual Montana	FF	40.5	Avitabile et al., (2016)	RS	12.4
Formações Pioneiras de Influência aluvial	FF	25.3	Santana et al., (2013)	FI	7.28
Floresta Estacional Semidecidual Aluvial	FF	40.5	Baccini et al., (2014)	RS	12.4
Floresta Estacional Semidecidual Submontana	FF	40.5	Baccini et al., (2014)	RS	12.4
Campo limpo	GF	5.50	Castro e Kauffman (1998)	FI	13.9
Savana Parque	GF	8.71	Santana et al., (2013)	FI	12.7
Savana Gramíneo-Lenhosa	GF	5.50	Castro e Kauffman (1998)	FI	13.9
Caatinga arbustiva	SF	33.6	Lima Júnior et al.,(2014)	FI	3.43
Savana	SF	16.5	Santana et al. (2013)	FI	22.6
Savana Estépica arbórea aberta/arborizada	SF	33.6	Lima Júnior et al.,(2014)	FI	3.43
Savana – Savana estépica	SF	33.6	Lima Júnior et al.,(2014)	FI	3.43
Savana arbórea aberta/ arborizada	SF	16.5	Santana et al. (2013)	FI	22.6
Savana arbórea densa / Florestada	SF	24.4	Santana et al. (2013)	FI	9.34

APPENDIX C

The results of soil organic carbon concentration (SOCC) presented high values in the top soil layers and low values in deeper layers for all LULCCs. In natural ecosystems, the SOCC was lower in CDO than for FOR, showing averages values between 0.54 ± 0.34 g kg^{-1} and 0.86 ± 0.54 g kg^{-1} in the 0-30 cm layer, while in FOR, the maximum average reached 1.38 ± 0.60 g kg^{-1} (Table C1). Among agricultural classes, the IRR areas showed 0.58 ± 0.20 g kg^{-1} at 0-30 cm, while the estimate in RAG was 0.47 ± 0.39 g kg^{-1} and equal to 0.34 ± 0.37 g kg^{-1} for PAST.

Table C1. Soil organic carbon concentration along profile (0-100 cm) for Cerrado Formations (CDO), Forest Formations (FOR), Rainfed Agriculture (RAG), Irrigated Agriculture (IRR), and Pasture (PAST) in g kg^{-1}.

LULCC	0-5	5-10	10-15	15-20	20-40	40-60	60-100
CDO	0.86(0.55)	0.86(0.54)	0.86(0.54)	0.69(0.46)	0.54(0.34)	0.37(0.27)	0.31(0.26)
FOR	1.38(0.60)	1.17(0.63)	1.03(0.55)	0.71(0.45)	0.64(0.43)	0.39(0.27)	0.30(0.22)
PAST	0.74(0.60)	0.61(0.49)	0.49(0.52)	0.46(0.47)	0.34(0.37)	0.26(0.31)	0.25(0.21)
IRR	1.17(0.38)	0.91(0.24)	0.84(0.26)	0.69(0.23)	0.58(0.20)	0.48(0.15)	0.40(0.10)
RAG	0.71(0.44)	0.68(0.41)	0.58(0.41)	0.43(0.36)	0.47(0.39)	0.28(0.21)	0.24(0.26)

* standard deviation is represented by values between parentheses

APPENDIX D

Table D1. Soil carbon stocks (Tg-C) estimates for Grande, Corrente and Carinhanha Basins for Cerrado formations (CDO), Forest formations (FOR), Rainfed Agriculture (RAG), Irrigated Agriculture (IRR), and Pasture (PAST) classes in OBahia Classification database.

LULCCs	1990		1997		2004		2011		2018	
	avg	std	avg	std	avg	std	avg	std	avg	std
Grande Basin	55.0 ±	14.3	53.9 ±	15.3	53.1 ±	15.2	53.3 ±	15.1	52.3 ±	14.8
FF	6.97 ±	2.07	6.18 ±	1.76	5.57 ±	1.48	7.67 ±	1.97	9.54 ±	2.40
SF	33.8 ±	9.77	30.7 ±	8.82	29.1 ±	8.35	27.8 ±	7.99	19.9 ±	5.69
GF	8.63 ±	2.47	7.02 ±	1.98	4.79 ±	1.34	1.95 ±	0.55	2.16 ±	0.60
RAG$_C$/PAST$_C$	0.29 ±	0.00	0.29 ±	0.05	0.33 ±	0.06	1.08 ±	0.20	2.44 ±	0.46
RAG$_C$	2.79 ±	0.00	4.96 ±	1.09	8.28 ±	2.15	10.1 ±	2.74	11.7 ±	3.24
IRR$_C$	0.08 ±	0.00	0.34 ±	0.05	0.51 ±	0.08	0.62 ±	0.10	0.97 ±	0.16
PAST$_C$	2.52 ±	0.00	4.38 ±	1.49	4.56 ±	1.71	4.04 ±	1.52	5.55 ±	2.30
Corrente Basin	24.9 ±	6.42	24.0 ±	6.8	23.6 ±	6.82	23.8 ±	6.79	23.2 ±	6.66
FF	3.96 ±	1.16	3.63 ±	1.00	3.81 ±	0.99	5.25 ±	1.32	3.49 ±	0.88
SF	8.45 ±	2.47	8.49 ±	2.42	7.15 ±	2.02	8.08 ±	2.27	8.10 ±	2.27
GF	9.79 ±	2.80	7.76 ±	2.18	6.91 ±	1.93	3.64 ±	1.02	3.29 ±	0.92
RAG$_C$/PAST$_C$	0.12 ±	0.00	0.11 ±	0.02	0.11 ±	0.02	0.28 ±	0.05	0.73 ±	0.14
RAG$_C$	1.24 ±	0.00	1.56 ±	0.36	2.91 ±	0.80	4.08 ±	1.17	4.84 ±	1.40
IRR$_C$	0.05 ±	0.00	0.11 ±	0.01	0.13 ±	0.02	0.20 ±	0.03	0.45 ±	0.07
PAST$_C$	1.26 ±	0.00	2.36 ±	0.82	2.60 ±	1.04	2.27 ±	0.93	2.31 ±	0.99
Carinhanha Basin	12.6 ±	3.38	12.2 ±	3.48	12.0 ±	3.49	12.0 ±	3.48	11.8 ±	3.48
FF	1.22 ±	0.37	1.31 ±	0.36	1.48 ±	0.38	1.77 ±	0.45	1.79 ±	0.45
SF	3.60 ±	1.05	3.71 ±	1.05	3.16 ±	0.89	4.40 ±	1.24	4.47 ±	1.25
GF	6.84 ±	1.96	5.77 ±	1.62	5.05 ±	1.41	3.25 ±	0.91	2.28 ±	0.64
RAG$_C$/PAST$_C$	0.04 ±	0.00	0.03 ±	0.01	0.03 ±	0.01	0.10 ±	0.02	0.34 ±	0.06
RAG$_C$	0.38 ±	0.00	0.42 ±	0.10	0.84 ±	0.24	1.12 ±	0.32	1.20 ±	0.35
IRR$_C$	0.01 ±	0.00	0.01 ±	0.00	0.01 ±	0.00	0.02 ±	0.00	0.12 ±	0.02
PAST$_C$	0.52 ±	0.00	0.98 ±	0.33	1.41 ±	0.57	1.33 ±	0.54	1.62 ±	0.70