A GIS approach to sustainable livestock planning from carbon dynamics analysis: a case study of a cattle ranch in Serra da Mantiqueira (Brazil)

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NOVA Information Management School

A GIS APPROACH TO SUSTAINABLE LIVESTOCK PLANNING

FROM CARBON DYNAMICS ANALYSIS

A case study of a cattle ranch in Serra da Mantiqueira (Brazil)

Dissertation supervised by

Pedro da Costa Brito Cabral

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DECLARATION OF ORIGINALITY

I declare that the work described in this document is my own and not from someone else. All the assistance I have received from other people is duly acknowledged and all the sources (published or not published) are referenced.

This work has not been previously evaluated or submitted to NOVA Information Management School or elsewhere.

Rio de Janeiro, September 26, 2019

Alexandre Dargains Auricchio de Oliveira

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UMA ABORDAGEM SIG PARA O PLANEJAMENTO SUSTENTÁVEL DA PECUÁRIA A PARTIR DA ANÁLISE DA DINÂMICA DO CARBONO

Estudo de caso de uma fazenda pecuarista na Serra da Mantiqueira (Brasil)

RESUMO

A avaliação da dinâmica do carbono como indicador de serviços ecossistêmicos de regulação climática, através da modelagem de diferentes cenários sobre mudanças de uso e cobertura do solo (LULC), é amplamente utilizada em estudos de conservação ambiental para apoiar processos decisórios atrelados a políticas públicas. Todavia, são raros os estudos em escala local que analisam a relação de impacto e custo-benefício da simulação de cenários agrícolas sustentáveis na prestação de serviços ecossistêmicos. Neste trabalho, realizamos a quantificação, a avaliação econômica e o mapeamento da captura e do estoque de carbono de cenários LULC passados (2007-2017) e futuros (2027), em uma fazenda pecuarista da Serra da Mantiqueira, para entender como diferentes mudanças de paisagens podem impactar o serviço de regulação climática e contribuir economicamente com o setor agrícola. Sob uma abordagem SIG, empregamos técnicas de detecção remota, para elaborar os mapas LULC, ferramentas de modelagem *Integrated Valuation of Ecosystem Services and Tradeoffs* (InVEST), para a construção dos cenários futuros e para avaliação das dinâmicas de carbono, e ferramentas de modelagem da família Sis para simular a produção resultante do manejo florestal. Todos os cenários avaliados promoveram o aumento da captura e do estoque de carbono na área de estudo, assim como revelaram oportunidades econômicas rentáveis associadas à sua implementação. A introdução de árvores de eucalipto no sistema de produção agropecuário é uma alternativa interessante para a diversificação e aumento de renda, contribuindo para o equilíbrio dos gases de efeito estufa (GEE) da atividade pecuária e agregando valor à produção. Esses resultados são úteis para apoiar o planejamento e o desenvolvimento de políticas de conservação ambiental e de produção agrícola sustentável.

A GIS APPROACH TO SUSTAINABLE LIVESTOCK PLANNING FROM CARBON DYNAMICS ANALYSIS

A case study of a cattle ranch in Serra da Mantiqueira (Brazil)

ABSTRACT

The assessment of carbon dynamics as indicator of climate-regulation ecosystem services (ES) through the modeling of different scenarios on land use and land cover (LULC) changes is widely used in environmental conservation studies to support the decision-making process regarding public policies. However, studies at local scales that address the subject under the farm property perspective, through impact and cost-benefit analyses of simulated sustainable farming scenarios on the provision of ecosystem services, are rare or nonexistent. In this paper, we performed the quantification, valuation and mapping of carbon capture and storage of past (2007-2017) and future LULC (2027) sustainable scenarios in a cattle ranch of Serra da Mantiqueira to understand how different LULC change scenarios may affect the provision of ES and contribute to economic opportunities to the farming sector. Under a GIS-approach, we used remote sensing techniques to LULC mapping, Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model for scenario building, carbon assessment and valuation, as well as Sis family software modeling for forest management production. All the sustainable scenarios contributed to the increase of carbon capture and storage in the study area, in addition to showing profitable economic opportunities arising from their implementation. The introduction of eucalyptus trees in livestock and agricultural production systems is an interesting alternative for diversification and income increase, contributing to the balance of greenhouse gases (GHG) from livestock activity and adding value to production. These results are useful to support the development and planning for both environmental conservation policies and sustainable farming production.

PALAVRAS-CHAVE

SIG

Armazenamento e Sequestro de Carbono

Modelo InVEST

Agropecuária Sustentável

Serviços Ecossistêmicos

Serra da Mantiqueira

KEYWORDS

GIS

Carbon Storage and Sequestration

InVEST model

Sustainable Farming

Ecosystem Services

Serra da Mantiqueira

ACRONYMS

AGB	Aboveground live Biomass
ARIES	Artificial Intelligence for Ecosystem Services
BCB	Banco Central do Brasil (Central Bank of Brazil)
BGB	Belowground live Biomass
C	Carbon
CAR	Cadastro Ambiental Rural (Rural Environmental Register)
CEPEA	Centro de Estudos Avançados em Economia Aplicada (Center for Advanced Studies in Applied Economics)
CH_4	Methane
CO_2e	Carbon dioxide equivalent
DBH	Diameter at Breast Height
DOM	Dead Organic Matter
EMATER-MG	Empresa de Assistência Técnica e Extensão Rural do Estado de Minas Gerais (Technical Assistance and Rural Extension Company of the State of Minas Gerais)
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuária (Brazilian Livestock-Agriculture Research Company)
ETS	Emission Trading System
FAO	Food and Agriculture Organization of the United Nations
GFW	Global Forest Watch
GHG	Greenhouse Gases

GIS	Geographic Information System
Gvces	Centro de Estudos em Sustentabilidade da Escola de Administração de Empresas da Fundação Getulio Vargas (Center for Sustainability Studies of the Business Administration School of Fundação Getulio Vargas)
ha	Hectare
HTML	Hypertext Markup Language
ICAP	International Carbon Action Partnership
IDE-Sisema	Infraestrutura de Dados Espaciais do Sistema Estadual de Meio Ambiente e Recursos Hídricos (Spatial Data Infrastructure of the State Environment and Water Resources System)
IFAD	International Fund for Agricultural Development
IFAG	Instituto Para o Fortalecimento da Agropecuária de Goiás (Institute for the Strengthening of Goiás Agriculture and Livestock)
IMAc	Incremento Médio Anual de carbono (Average annual carbon increment)
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IPCC	Intergovernmental Panel on Climate Change
IPEF	Instituto de Pesquisa e Estudos Florestais (Forestry Research and Studies Institute)
ITPS	Intergovernmental Technical Panel on Soils
LEF	Legally Exploitable Forest
LR	Legal Reserve
LUCI	Land Utilization and Capability Indicator

LULC	Land Use and Land Cover
LULCC	Land Use and Land Cover Changes
Mg	Megagram
NGO	Non-Government Organization
NPV	Net Present Value
OLI	Operational Land Imager
PES	Payments for Environmental Services
Pg	Petagram
PPA	Permanent Preservation Area
REED+	Reducing Emissions from Deforestation and Forest Degradation
SNIF	Sistema Nacional de Informações Florestais (Brazilian National Forest Information System)
SOM	Soil Organic Carbon
TM	Thematic Mapper
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations Children's Fund
VHR	Very-High Resolution
VM	Voluntary Market of Carbon
WFP	World Food Programme
WRI	World Resources Institute

INDEX OF THE TEXT

INDEX OF FIGURES

INDEX OF TABLES

1 INTRODUCTION

According to the recent report published by Food and Agriculture Organization of the United Nations (FAO), the gains made in ending hunger and malnutrition are being lost through climate variability and exposure to more complex, frequent and intense climatic extremes (FAO, IFAD, Unicef, WFP, 2018). Thus, it is imperative to accelerate and increase actions to strengthen the resilience and adaptability of food systems to achieve the goal of a planet without hunger and malnutrition by 2030 (FAO, IFAD, Unicef, WFP, 2018). One of these actions is limiting global temperature rise to 1.5 Celsius degrees, instead of 2.0 degrees (UNFCCC, 2016). Data from the Global Forest Watch (GFW) project, coordinated by the NGO World Resources Institute (WRI) with the University of Maryland, USA, reinforce the importance of land use and land cover in this context and show that preserving green areas could represent up to 30% of the solution to problems related to climate change (GFW, 2018). The latest report published by the Intergovernmental Panel on Climate Change (IPCC) shows that, with some effort, it is possible to contain the rise in temperature to 1.5 degrees Celsius (IPCC, 2018). This implies promoting severe reductions in gas emissions from all sectors. In this regard, changes related to land use and land cover (LULC) represent major challenges for the sustainable management of its various applications, such as carbon storage and sequestration (IPCC, 2018).

The ability to reduce carbon emissions and increase carbon sequestration are key factors in controlling the largescale impacts of man-made processes such as climate change and their effects on other ecosystem services (IPCC, 2014). Carbon storage and carbon sequestration are indicators of ecosystem services used to measure productive responsiveness and ecological resilience to changes in terrestrial ecosystems (Hicks et al., 2014; Teillard et al., 2016). Both are often used in studies as indicators in the spatial assessment of ecosystem services, i.e. climate regulation (de Groot et al., 2010; Maes et al., 2016; Vargas et al., 2019). Consequently, carbon has been the focus of numerous strategies which include cap-and-trade schemes, carbon taxation and payments for environmental services (PES) (Castro et al., 2018; Zammit, 2013).

According to Ezzine-de-Blas *et al.* (2016), PES have become an increasingly popular conservation incentive tool and they are being implemented on multiple geographical scales around the world. The PES central idea is that external environmental services beneficiaries make direct, contractual and conditional payments to local landowners and users in exchange for the adoption of practices to ensure the conservation and restoration of the ecosystem (Wunder, 2005). Among the different types of environmental services in evidence, the storage and sequestration of carbon is one of the types that currently stand out for showing remarkable commercial scale (Wunder, 2005). Several successful PES programs based on carbon have been established around the world, such as in Brazil (Börner et al., 2017; Castro et al., 2018; Matzdorf et al., 2014; Pagiola et al., 2013; Zammit, 2013). Due to its voluntary and directly measurable character (e.g. additional tons of carbon stored), which means a clear and objective scope of what is being bought, PES can be considered an alternative and an economic incentive for landowners in favor of the desired land use (Wunder, 2005).

The quantification, mapping and evaluation of ecosystem services are of great interest to environmental policy and land use planning (Parron et al., 2015a). They can be implemented through a spatially explicit manner, which is an approach widely disseminated in the scientific literature (Maes, Joachim; Hauck, Jennifer; Paracchini, 2012; Nelson et al., 2009; Serna-Chavez et al., 2014). To support these practices there are some tools available for general use that provide economic-ecological modeling, facilitating spatially explicit assessment (Jackson et al., 2017; Pakzad et al., 2015). These tools, such as ARIES - Artificial Intelligence for Ecosystem Services (Villa et al., 2014), InVEST - Integrated Valuation of Ecosystem Services and Tradeoffs (Sharp et al., 2016) and LUCI - Land Utilization and Capability Indicator (Jackson et al., 2013), perform an important role by providing information about ecosystem services, through the integration of spatially explicit indicators in the assessment. They also support landowners' decision making by providing resources to the analysis of potential impacts of future land use change scenarios (de Groot et al., 2010). The most common approach to map and model the supply of ecosystem services, such as climate regulation, has been the quantification of carbon stocks associated with soil and vegetation pools, and their behavior over time and space due to changes in LULC. (Jackson et al., 2017; Nelson et al., 2009; Pakzad et al., 2015; Parron et al., 2015a; Pavani et al., 2018; Zhang et al., 2017).

LULC are important factors that affect the delivery of ecosystem services (Parron et al., 2015a). LULC changes (LULCC) occur more rapidly in the tropics, where an imbalance between deforestation and secondary forest regrowth has significant consequences for the global carbon cycle (Hansen et al., 2013). In the last decade, around 30 percent of the Earth's land surface was dedicated to livestock production through pastures (≈ 25%) and feed crops (≈ 5%) (Monfreda et al., 2008; Ramankutty et al., 2008). A recent report has shown that Brazil led the deforestation rates among tropical countries in 2014 and released, approximately, 1.6 Gt (gigatons) CO_2e (carbon dioxide equivalent) to the atmosphere, mostly due to land use change caused by the cutoff of native forests and their replacement by pastures (Gurgel and Costa, 2015). Facing a scenario where dietary changes in emerging countries have been significantly increasing global demand for animal products, improving production while limiting its negative impacts on biodiversity becomes a challenge to the livestock sector (Teillard et al., 2016).

However, it is complicated to isolate and to quantify the impact of livestock-related greenhouse gases (GHG) emissions on biodiversity (Teillard et al., 2016). Livestock can also have a positive effect on biodiversity in the face of climate change (Klein et al., 2004). A growing number of studies show that sustainable initiatives like reforestation (Campanha, Mônica Matoso; da Costa, Thomaz Correa e Castro; Neto, 2017; Jandl et al., 2006; Oliveira et al., 2008); implementation of agroforestry systems (Amézquita et al., 2005; Jandl et al., 2006; Pandey, 2002); the introduction of *urochloa* (*brachiaria*) pastures (Amézquita et al., 2005; Rosendo and Rosa, 2012; Segnini and Milori, 2007); and the recovery of degraded pastures (Amézquita et al., 2005; Segnini et al., 2019; Seó et al., 2017) can mitigate the negative effects of livestock production and even represent an opportunity to the provision of ecosystem services. The effective transformation of this scientific evidence into public policy, or into public information to subsidize a proper and sustainable land use planning, can help identify and implement carbon sequestration strategies. One way to address this challenge is to model the consequences of different scenarios on LULCC that reflect different management practices, such as natural areas conservation, agriculture, forestry and livestock practices, on carbon emissions (Bottalico et al., 2016; Garrastazú et al., 2015; Levrel et al., 2017; Liang et al., 2017; Nelson et al., 2009; Pavani et al., 2018; Tomasso and Leighton, 2014). The comparative analysis of alternative scenarios can provide information to support the decision-making process regarding public policies, enabling effective communication of these policies and their rationales to gain public buy-in (Bottalico et al., 2016; Malczewski, 2006; Zawadzka et al., 2017).

Carbon storage and sequestration, as both a regulatory policy and an economic opportunity, should be analyzed at broad scales as well as at the regional and local scale (Nelson et al., 2009; Serna-Chavez et al., 2014). However, studies at local scales, which address the subject under the farm property perspective through impact and cost-benefit analyses of simulated sustainable farming scenarios on the provision of ecosystem services, are rare or nonexistent. These studies could help the sector by providing key information to the planning and decision-making processes related to sustainable land management. This study fills this gap by providing a comprehensive case study for the Serra da Mantiqueira, in Brazil. Given their biological importance and being considered a priority for the conservation of endemic springs and species (Cunha and Guedes, 2013; Le Saout et al., 2013), many environmental projects have been developed in Serra da Mantiqueira (Pagiola et al., 2013) in order to reverse the damage caused by deforestation throughout its historical occupation until the end of the twentieth century (Mendes Jr, 1991; Fundação SOS Mata Atlântica/INPE, 2019). In this context, our study contributes to the discussion of LULC changes and their impact on the local provision of ecosystem services. It also assesses the way the implementation of different sustainable initiatives in the farming sector, based on future scenarios analysis, can affect carbon storage and sequestration indicators, as well as contribute economically to the sector.

The objective of this study is, based on a geographic information system (GIS) approach, to analyze the carbon balance as a result of past and future LULCC scenarios in a cattle ranch of Serra da Mantiqueira, as well as to assess the different economic opportunities arising from its implementation, in order to support the development of sustainable farming planning. The results are expected to broaden our understanding of how different scenarios of LULCC can contribute or affect the provision of ecosystem services and the generation of economic opportunities to the farming sector, as well as provide relevant information to the planning of sustainable farming.

2 MATERIALS AND METHODS

2.1 STUDY AREA

The study was conducted in a cattle ranch, a 971 ha mountain area, which intersects the districts of Bocaina de Minas and Carvalhos (Figure 2.1), located in the state of Minas Gerais, southeast Brazil (lat 22°09’18”S to 22°06’36”S, long 44°27’44”W to 44°30’29”W). The region ranges from 1150 to 1800 meters in altitude, in a warm and temperate climate. Summers are rainy, while winters have very little rain. The average temperature is 13.6 °C in the coldest months and 20°C in the hottest months, with an average annual rainfall of 2077 mm (Guimarães et al., 2010). According to the Köppen-Geiger classification, this climate can be categorized as Cwb, featuring a temperate climate with cool and humid summer at an altitude of over 1100 m (de Sá Júnior et al., 2012; Dubreuil et al., 2018).

The area is part of the Serra da Mantiqueira, an ecosystem of the Atlantic Forest biome. It is characterized by the presence of Montane Semideciduous Seasonal Forest; High montane Dense Humid (*Ombrophylous*) Forest; Montane Dense Humid Forest; Rupestrian Fields; *Urochloa* (Brachiaria) pastures; and plantations of *Eucalyptus Grandis spp*. In 2017, the study area consisted of 39.48% of High Montane Dense Humid Forest (Dl) and 10.27% of Montane Dense Humid Forest (Dm), according to the patterns established by the vegetation classification of 2009 Forest Inventory (IDE-Sisema, 2019), conducted by the State Forest Institute of Minas Gerais.

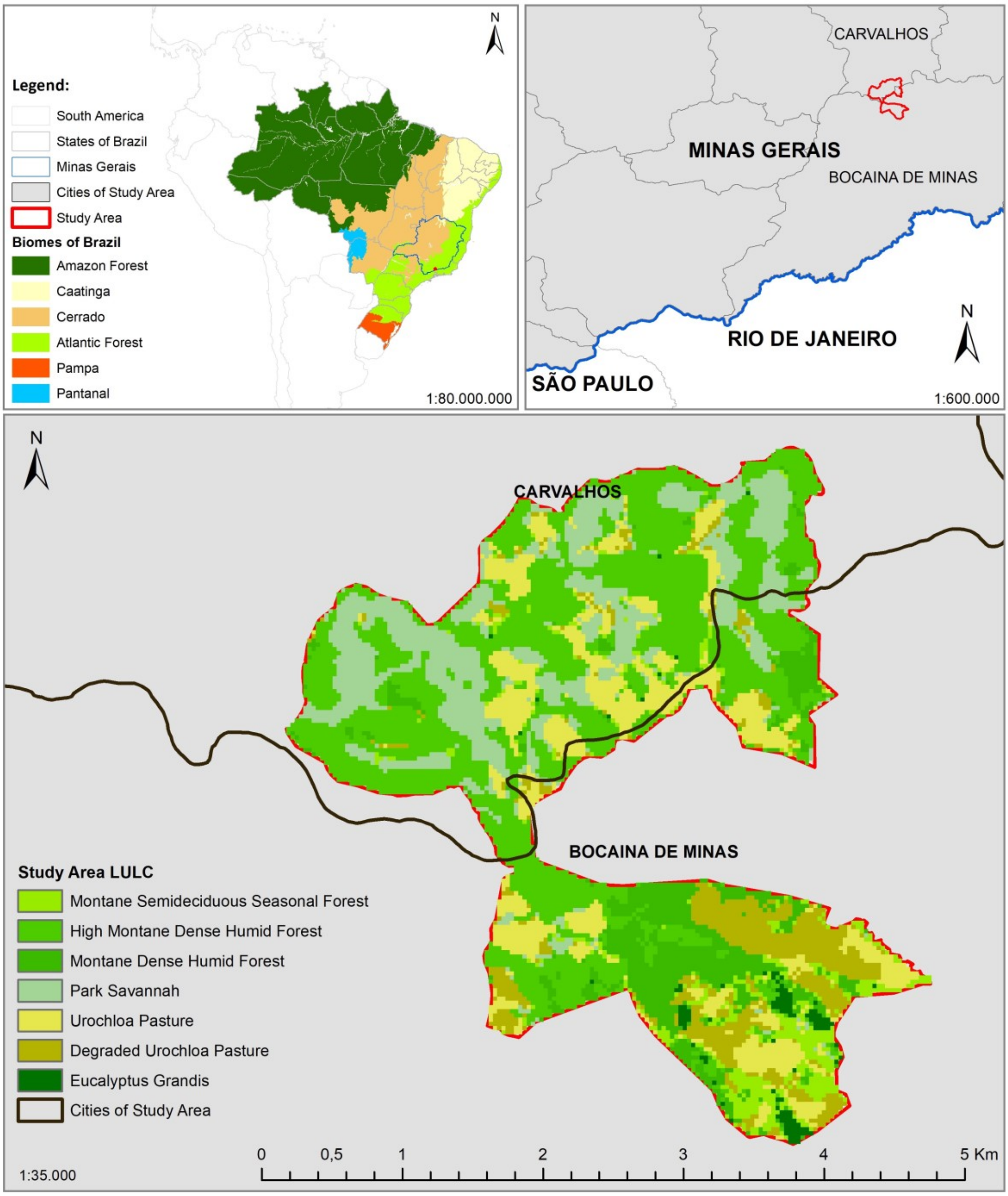

Figure 2.1 – Study area location.
Notes: Brazil with the indication of its biomes, and the state of Minas Gerais (upper left); the study area location regarding its state and city boundaries (upper right); and a closer perspective of the study area limits, overlaid by 2017 LULC map (lower right).

The Dense Humid Forest, also known as Tropical Rainforest, is characterized by dense vegetation in all strata (arboreal, shrubby, herbaceous and lianas) consisting of ferns, arborescent trees, bromeliads and palm trees (SNIF, 2019). The Montane Semideciduous Seasonal Forest (Fm), covering 5,65% of the area, has its vegetation conditioned by the dual climatic seasonality: a tropical one, with intense summer rains followed by severe drought and another subtropical one, without dry season, but with physiological drought caused by intense winter cold, when the vegetation loses its leaves. The Rupestrian Field (18,65%), classified as Park Savannah (Sp) by the Brazilian Institute of Geography and Statistics (IBGE), is characterized by low trees and spaced shrubs. It is associated with grasses and usually has markedly tortuous and grayish trunks and branches (SNIF, 2019). The brachiaria pasture is resistant to leafhoppers and is characterized by high forage production, persistence, good regrowth, tolerance to cold, drought and fire. It is recommended for breeding, rearing and fattening cattle. It is also well accepted by buffalo, sheep and goats. It supports rotational grazing, hay production and silage (Nunes et al., 1984). Its coverage in the study area is divided into cultivated pastures (Pa) and degraded pastures (Pd). The first one, representing 15.06% of the total area, supported by adequate management, and the second one with 9.66%. The *Eucalyptus Grandis*, covering 1.24% of the area, is characterized by very tall (45 to 55 meters) and thick (1.2 to 2m DBH) trees usually with a smooth shaft in the upper 2/3 or 3/4 of the stem (IPEF, 2019).

The predominant soil is the dystrophic red-yellow latosol, with the presence of dystrophic humic cambisol in the high rupestrian complexes, according to the criteria of the Brazilian Soil Classification System (Santos et al., 2013). Beef cattle raising is the main activity of the farm, focusing on cattle breeding. The current cattle population is approximately 200 Nellore cattle and 7 Angus breeders. Besides the native forests, the study area has a vast hydric richness (Figure 2), composed of dozens of streams and springs, which turn the site into a potential point of interest for the implementation of payment for environmental services (PES) projects.

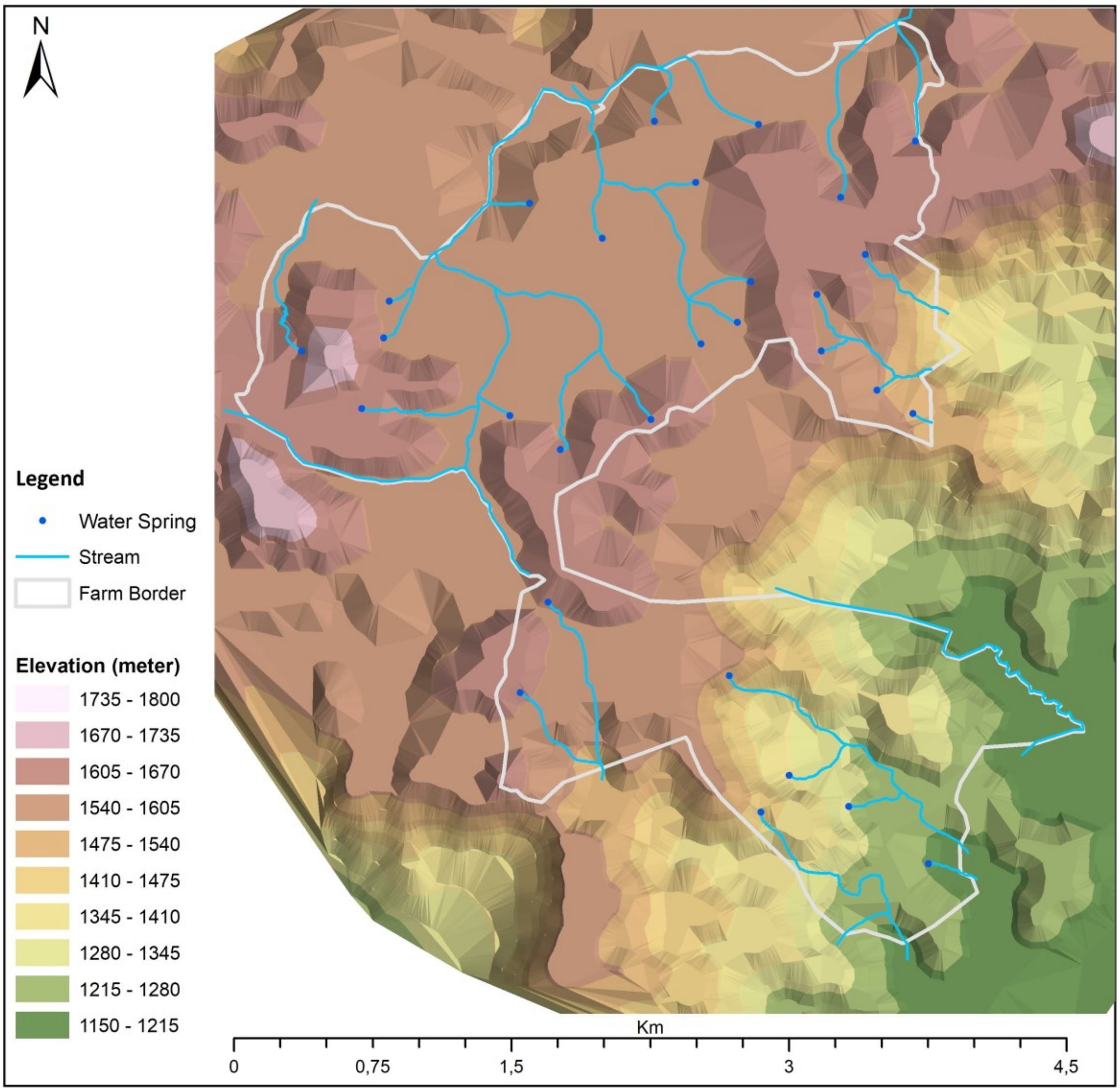

Figure 2.2 – Study area digital elevation model.

2.2 RESEARCH FRAMEWORK

We assessed the impacts of landscape change in the study area through the quantification, valuation and mapping of carbon storage and sequestration, considering the LULC changes observed between 2007 to 2017 and the future changes based on four sustainable scenarios projected for 2027.

In summary, we did extensive research about the study area regarding its geographic characteristics (e.g. biodiversity, topography, climate, hydrography, soil, etc.) and on the subject under study. In addition, we extracted, transformed and loaded all the data required to perform the work (e.g. shapefiles of study area limits, streams, water springs, preservation areas, isolines, etc.). In sequence, we developed the study area

LULC maps in the observed periods (2007 and 2017) and we generated alternative LULC maps related to four scenarios predicted for 2027 (Subsections 2.2.1 and 2.2.2).

The InVEST Carbon model (version 3.7) was used for carbon dynamics assessment, economic valuation and scenario building (Nelson et al., 2014; Sharp et al., 2016). InVEST is a set of models used to quantify, map and value the services provided by ecosystems. It aims to support decision makers to explore the likely outcomes of alternative management and climate scenarios and to assess tradeoffs among sectors and services. The toolkit currently includes more than a dozen distinct InVEST models, suitable for terrestrial, freshwater and marine ecosystems.

In order to support the model execution, we provided LULC spatial data for the three dates under analysis, the carbon data on above (AGB) and belowground live biomass (BGB), dead organic matter (DOM) and soil organic carbon (SOC) for each LULC class (Subsection 2.2.2). These data are used to estimate the amount of carbon currently stored in a landscape and the amount of carbon sequestered overtime (Nelson *et al.*, 2014). In addition, to contribute to the decision-making process, we conducted the PES scheme assessment under two different approaches and the sale of eucalyptus wood as an economic opportunity for scenarios 3 and 4 (Subsection 2.2.3). Aiming to obtain the income of eucalyptus timber production per hectare, we used two forest management simulators (SisEucalipto and SisILPF), which estimate the average timber volumes per hectare, as well as set the timber commercial use volumes according to its diameter (energy and sawmill). Finally, the results were compiled, analyzed and later compared with similar studies to foster a rich reflection and discussion on the subject (Subsection 2.2.3). Figure 2.3 shows the general work flowchart with the main processes carried out during the study (See ANNEXES for further details).

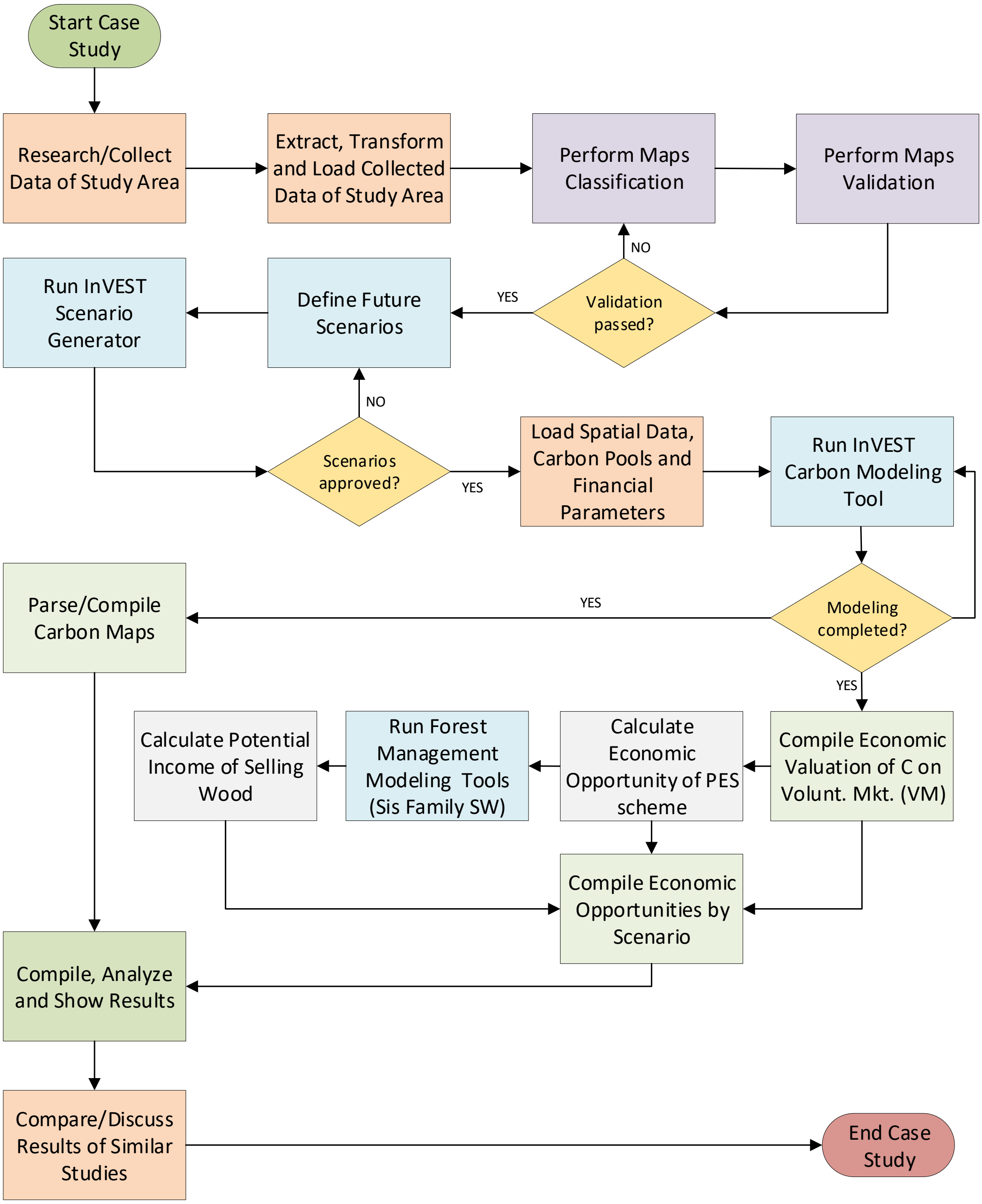

Figure 2.3 – Case study general flowchart.

2.2.1 LULC mapping and generated scenarios

The first stage of the study consisted of gathering information about the study area through CAR (an acronym in Brazilian Portuguese which stands for "Cadastro Ambiental Rural" or "Rural Environmental Register" in English), a mandatory federal registration that delimits areas designated as legal reserve (LR) and permanent preservation areas (PPAs), as well as native vegetation, and anthropic areas (Brasil, 2012). This information, along with conducting extensive research, allowed us to obtain geospatial data and the information required to perform the subsequent steps (e.g. study area boundaries, springs, watercourses, LULC classes, topography, climate, soil type, among others).

The LULC mapping used two orthorectified images, scene 218/75 of July 2007 and September 2017, from Landsat-5 Thematic Mapper (TM) and Landsat-8 Operational Land Imager (OLI) satellites, respectively. Both images have a spatial resolution of 30 meters, have no clouds and cover the entire study area. The training data were collected based on visual interpretation of very high resolution (VHR) spatial images taken by World View 01 satellite on June 20, 2008 (0.5 m resolution) and taken by Word View 03 on September 12, 2017 (1 m resolution). These images were provided by Digital Globe Foundation (Digital Globe, 2019) and were also used as reference data in the accuracy assessment procedures. We selected a different number of samples for each LULC class, considering the proportionality of each one concerning the total area. For the map classification, we used *maximum likelihood* supervised algorithm and majority filter (8 x 8 pixels) was applied for the refinement of the LULC maps, reassigning the LULC class to the center of the square (Caprioli and Tarantino, 2001). A confusion matrix was built to compare the classification with ground-truth data obtained through a stratified random sampling approach based on the representativeness of the LULC class (Adefioye, 2014; Banko, 1998; Foody, 2002). The total number of samples (reference or control points) for each map was (Neves, Strauch and Ajara, 2017; Hall *et al.*, 2018):

$$\boldsymbol{T_s} = (10.\ \boldsymbol{S_c}).\ \boldsymbol{S_c}$$

Equation 1 – Total number of samples for accuracy assessment

where $\boldsymbol{T_s}$ is the total number of samples and $\boldsymbol{S_c}$, the total amount of classes on each map. After building the confusion matrix, we computed some statistics related to accuracy assessment (Classes' accuracy, User's accuracy, Producer's accuracy and Mapping accuracy) as well as the overall accuracy and the overall *Kappa* coefficient, which is a measure of agreement or accuracy (Congalton and Green, 1999).

The software used to support the activities performed at this stage was ArcGIS Desktop, version 10.5.1.

In order to understand the impact of different landscape changes on carbon storage and sequestration dynamics, we used the InVEST Scenario Generator module to create four alternative scenarios for the year 2027 (Table 2.2). The four scenarios (Figure 2.3) were designed based on best practices for environmental service delivery in agricultural and forestry systems in the Atlantic Forest biome (Parron et al., 2015a). Meetings were also held with the farm's owners to analyze the feasibility of implementing these scenarios in the medium and short term.

- **Preservation and natural forest regeneration (Scenario 1)**: simulates the preservation of the current forest area (2017) and the natural regeneration of forest loss (25 ha) of the last ten years over the pasture edges. We define it as a low management scenario and the base for the next three alternative scenarios.
- **Recovery of degraded pasture (Scenario 2)**: simulates the preservation of the current forest area (2017) and the natural regeneration of forest loss (25 ha) over degraded pastures and the recovery of remaining degraded *urochloa* (*brachiaria*) *brizantha* pastures (40 ha), indicating a moderate management level scenario.
- **Forest plantation (Scenario 3)**: simulates scenario 1 and the planting of an additional 60 ha of *eucalyptus grandis* over pastures, with 2 x 3 m spacing.
- **Silvopastoral system implementation (Scenario 4)**: simulates scenario 1 and the implementation of 60 ha of silvopastoral system (brachiaria pasture + *eucalyptus grandis*) with 8 x 4 m spacing. Scenarios 3 and 4 demand a more intensive management level.

Thus, a total of 8 classes were defined for LULC maps (Table 2.2): Montane Semideciduous Seasonal Forest (Fm); High montane Dense Humid Forest (Dl); Montane Dense Humid Forest (Dm); Park Savannah (Sp); *Urochloa* (*Brachiaria*) Pasture (Pa); Degraded Brachiaria Pasture (Pd); *Eucalyptus Grandis* (Eu); and Silvopastoral system (Si).

2.2.2 Carbon storage and sequestration

According to Liang et. al. (2017), the carbon storage $S_{m,\,i,\,j}$ for a given grid cell *(i, j)* with land use type *m* can be calculated as:

$$C_{m,\,i,\,j} = A \times (Ca_{m,\,i,\,j} + Cb_{m,\,i,\,j} + Cs_{m,\,i,\,j} + Cd_{m,\,i,\,j})$$

Equation 2 - Carbon storage per grid cell.

where *A* is the actual area of each grid cell (30 m) and $Ca_{m,\,i,\,j}$, $Cb_{m,\,I,\,j}$, $Cs_{m,\,i,\,j}$, and $Cd_{m,\,i,\,j}$ represent the densities of the referred carbon pools (Mg C ha^{-1}) for grid cell (i, j) with land use type *m*. Thus, carbon storage *C* and sequestration *S* across the region can be calculated as:

$$\sum^{n}{}_{\mathbf{m=1}} \mathrm{C}_{\mathbf{m,\,i,\,j}}$$

Equation 3 - Carbon storage per region

$$S = C^{T2} - C^{T1}$$

Equation 4 – Carbon sequestration per region

where C^{T2} and C^{T1} indicates static carbon storage at years *T2* and *T1* (T2 > T1) respectively.

Carbon data required to run the model was obtained for each of these pools through careful literature research (Table 2.1). Carbon storage information for each LULC class was estimated for four pools: AGB; BGB; DOM; and SOC. Even though reference values for carbon pools are available in InVEST for different land uses, we chose to prioritize regional and local values with similar topographic and edaphoclimatic characteristics to the study area. These data were obtained from official sources, academic thesis and scientific papers. This approach increases the reliability of the research and its results since significant discrepancies were found between what was provided by the InVEST model and those found in the literature for the study area (InVEST, 2019).

The method adopted to obtain carbon values is supported and used by some authors (Brown, 2002; Gibbs et al., 2007; Paixão et al., 2006). According to Gibbs (2007), the use of literary sources to acquire carbon stock values, as well as correlating carbon pools to estimate carbon stock, is a common practice and can generate adequate estimates. Gibbs (2007) and Brown (2002) used the correlation of 20% between root biomass and aboveground forest carbon stock as an example, while litter carbon stock is generally accepted as equivalent to 10-20% of aboveground forest carbon, approximately. Paixão et al. (2006) applied correlation factors, where dead organic matter and root biomass contribute, on average, with 12.26% and 20.68% of total carbon, respectively. As we did not find values for all carbon compartments, we applied the correlations used by the authors.

LULC class	AGB	Source	BGB	Source	SOC (1m)	Source	DOM Dead	Source
Fm	48.78	(SNIF, 2019)	9.76	(SNIF, 2019)	114.72	(Segnini et al., 2019)	4.88*	(Gibbs et al., 2007)
Dl [1]	63.5	(SNIF, 2019)	15	(SNIF, 2019)	146.4	(Parron *et al.*, 2015)	10.6	(Parron *et al.*, 2015)
Dm [1]	63.5	(SNIF, 2019)	15	(SNIF, 2019)	146.4	(Parron *et al.*, 2015)	10.6	(Parron *et al.*, 2015)
Sp	2.44	(SNIF, 2019)	9.83	(SNIF, 2019)	90.46	(Morais et al., 2013)	0.24*	(Gibbs et al., 2007)
Pa	5	(InVEST)	4	(InVEST)	142.81	(Segnini et al., 2019)	1	(InVEST)
Pd	5	(InVEST)	4	(InVEST)	99.88	(Segnini et al., 2019)	1	(InVEST)
Eu	81.8	(Scolforo, J. R., 2008)	25.36*	(Paixão et al., 2006)	112.89	(Gatto et al., 2010)	14.72*	(Paixão et al., 2006)
Si	75.14[1]	(Schettini et al., 2017)	23.3*	(Paixão et al., 2006)	393.7	(Tonucci et al., 2011)	13.52*	(Paixão et al., 2006)

Table 2.1 - Carbon stock values (Mg C/ha) and respective sources for each LULC class and carbon compartment. Note: * - Value calculated according to the author (see source column); [1] - Values regarding dense humid forest, due to the lack of enough data in the literature the for Dl and Dm forest subformations; The value in parentheses refers to the depth of the soil considered.

2.2.3 Economic valuation

Regarding the economic valuation model, to support the decision-making process from the perspective of financial opportunities, we based our analysis on three complementary approaches.

Firstly, we used the historical average price of carbon US$ 5.9/tCO_2 (US$ 21.64/tC [2]) traded on the voluntary market (Peters-Stanley et al., 2013). Although the InVEST model strongly recommends using the social value of carbon (Nelson et al., 2014), we decided to use the voluntary market, because it is accessible (Goldstein, 2015) and, despite having a large oscillation due to several factors such as project costs, buyer's

[1] Value calculated for a ten-year eucalyptus, from the average annual carbon increment rate (IMAc), 6.27Mg C ha^{-1} $year^{-1}$, and the value of carbon stock in a six-year eucalyptus (50.1Mg C ha^{-1}).

[2] Obtained from the conversion factor 0.2727, calculated by the relationship between the molecular weight of carbon dioxide and carbon (44/12) (Spellman, 2015).

preferences and the volume of the transaction (Hamrick and Gallant, 2018), it is in line with the prevailing and expected prices for the region, even when compared to other payment schemes. For example, the price adopted is aligned with Norway's International Climate and Forest Initiative, which made payments of US$5/t$CO_2$ for the Brazilian Amazon Fund, a REDD+ payment scheme (McNeish et al., 2011). The same can be observed in Latin American countries where US$5/tCO2 carbon taxes, over fossil fuels used for combustion (Colombia) and over air emissions from contaminating compounds (Chile), were implemented in 2017 (World Bank et al., 2017). Brazil is currently assessing different carbon pricing instruments, including an emission trading system (ETS) and a carbon tax (ICAP, 2019). Since 2013, a group of leading companies has been participating in a voluntary ETS simulation to gain experience and develop proposals for emission trading system in the country that can reduce national GHG emissions at the lowest possible cost (ICAP, 2019). According to information presented by Votorantim Cimentos (one of the group's participating companies) at the Latin American Carbon Price Forum, on June 25 and 26, 2018, the estimated price for Brazil, between 2020 and 2025, is US$ 5/tCO_2 approximately (GVces, 2018) , which is also similar to the historical average price of carbon used in this study.

To determine the market discount rate of 6% we used the average effective inflation between 2007 and 2017, released by the Central Bank of Brazil (BCB, 2019a). This rate is very close to the base interest rate recorded at the end of 2017 by the same institution (BCB, 2019b), which allowed us to apply the same discount rate for both the observed and future scenarios. The annual adjustment rate of 3.4% on carbon price was estimated for the future scenarios based on the average of carbon tax price change in Colombia, between 2017 and 2019 (World Bank, 2019).

As a second approach, considering the growing number of PES schemes in Brazil observed in the variety of local and regional programs in various states and municipalities (Pagiola et al., 2013), we assessed the economic benefits on the total forest area and on the total of legally exploitable forest (LEF) of the study area (Table 2.2). LEF can be understood as forest areas not belonging to permanent preservation areas (PPAs) and legal reserve areas (LR). Given the hydrological characteristics of the study area and its proximity to the "Conservador das Águas de Extrema" project, in Minas Gerais, we used the value[3] of US$82.91 ha^{-1} $year^{-1}$ paid by the project in 2016 (Pagiola et al., 2013). Even though the referred project pays for the total property area, we decided to use a more conservative approach based on other PES projects that usually solely consider the native forest area (Pagiola et al., 2013). The annual adjustment rate of 1.33% was calculated based on historical payments made between 2006 and 2016 (Pagiola et al., 2013; Secretaria de Meio Ambiente de Extrema, 2017).

Identification	Area (ha)	Area (%)
PPAs	147.63	15.20
LR	239	24.61
Overlapping Areas (LR over PPAs)	31.92	3.28
Total Protected Forest	**354.71**	**36.53**
LEF (2017)	180.43	18.58
LEF (2027)	205.45	21.15
Total Forest Area	**560.16**	**57.69**

Table 2.2 - Size of forested areas and their percentage proportion to the study area.

Lastly, based on Paixão et al. (2006) and Oliveira et al. (2008) studies, we also calculated the economic opportunity of selling eucalyptus timber, considering the costs[4] per hectare in 2017 (Table 2.3) of a low-tech, low-resource reforestation project, as well as the market prices of stand timber for firewood (US$9.10/$m^3$) and for sawmill (US$37.81/m^3) (CEPEA, 2017). We chose not to consider the annual adjustment rate of the standing timber price since we did not find a pattern in the eucalyptus market prices that could contribute to the calculation of its price over time. According to Rocha et al. (2015), eucalyptus price variability, between the period of low and high prices, results in great uncertainty for producers and consumers over the years.

[3] Amount related to the conversion of R$262.00 (Brazilian reais) at the exchange rate of 3.16, registered on August 12, 2016 by the Central Bank of Brazil (BCB, 2019a).

[4] The costs and stand timber prices were converted into American dollars at the exchange rate of 3.30, as recorded on December 28, 2017 by the Central Bank of Brazil (BCB, 2019a).

Item	Scenario 3 (US$/ha)	Scenario 4 (US$/ha)
Planting	533.07	355.22
Land annual cost *	62.72	62.72
Maintenance (first year)	128.99	128.99
Maintenance (annual cost)	45.55	40.11
Total for 10 years	**1744.76**	**1512.51**

Table 2.3 - Estimated operational costs. Sources: EMATER-MG, 2019 (land annual cost) and IFAG, 2017.
Note: * - The annual cost of land was calculated by multiplying the value of the land by the interest rate used (Alves et al., 2015). Our study used the amount of R$3,000/ha for the annual cost of land in the district of Bocaina de Minas (EMATER-MG, 2019) and an annual interest rate of 6.90% (BCB, 2019b). These data refer to the end of 2017.

In order to estimate the average timber volumes per hectare, we used the forest management software SisEucalipto, for scenario 3, and SisILPF, for scenario 4 (EMBRAPA, 2019). Provided by the Brazilian livestock-agriculture research company (EMBRAPA), the Sis family software is a set of free simulators for management, economic analysis, modeling, growth and production of planted forests used to assist in thinning planning (EMBRAPA, 2019; Oliveira, 2019). In order to obtain the eucalyptus growth and yield forecasts for each scenario, as well as the total wood volumes for energy and sawmill use according to DBH (diameter at breast height) classes, we provided the inventory forest data required by both simulators (Table 2.4).

Although eucalyptus thinning generally occurs around 7 years (Oliveira et al., 2008; SCOLFORO, 2008), and considering that economic rotation can provide lower profitability when no thinning is performed, (Soares et al., 2003), we chose to simulate the thinning of 40% of the planted area in the tenth year.

The quantitative economic criteria considered for scenario analysis was the net present value (NPV), which represents the net value, or benefit, over the useful life of a given project (Cavatassi, 2004). The economic assessment results were consolidated and presented under two approaches: economic influence on the study area; and economic influence on landscape change, making it possible to compare them with the farm's annual operating cost[5] (US$ 47.43 ha^{-1} $year^{-1}$), recorded in 2017.

Parameters	**Scenario 3 (SisEucalipto)**	**Scenario 4 (SisILPF)**
Simulation	*E. Grandis*	ILF - *E. Grandis*
Site index	30 m	30 m
Trees planted per hectare	1667	312
Initial survival	75% *	75% *
Listings option	Generate results for ages 1 to 10, every 1 year	
Diameter Class Range for Production	4 cm	NR
Minimum dimensions of use for sawmill	15 cm (diameter) x 2.4 m (length)	
Minimum dimensions of use for energy	3 cm (diameter) x 1.2 m (length)	
Number of tree rows	NR	1
Distance between tree rows	NR	8 m
Planting Homogeneity	NR	medium

Table 2.4 – Inventoried forest data for scenarios 3 and 4. ILF: Integrated Livestock-Forestry system. NR: Not required by the software. * Average survival rate of *eucalyptus grandis* found by Parron *et al.* (2015).

[5] Amount related to the division of the annual cost (R$152,000.00) by the total farm area (971 ha) and subsequent conversion to American dollars at the exchange rate of 3.3, as recorded on December 28, 2017 by the Central Bank of Brazil (BCB, 2019a).

3 RESULTS

3.1 LULC MAPS AND FUTURE SCENARIOS

LULC maps revealed the landscape changes over time and in different scenarios predicted for 2027 (Figure 3.1). Park savannah was the LULC class with the largest area losses due to *urochloa* pasture advancement, mainly in the northern region of the study area (Figures 3.1 and 3.2).

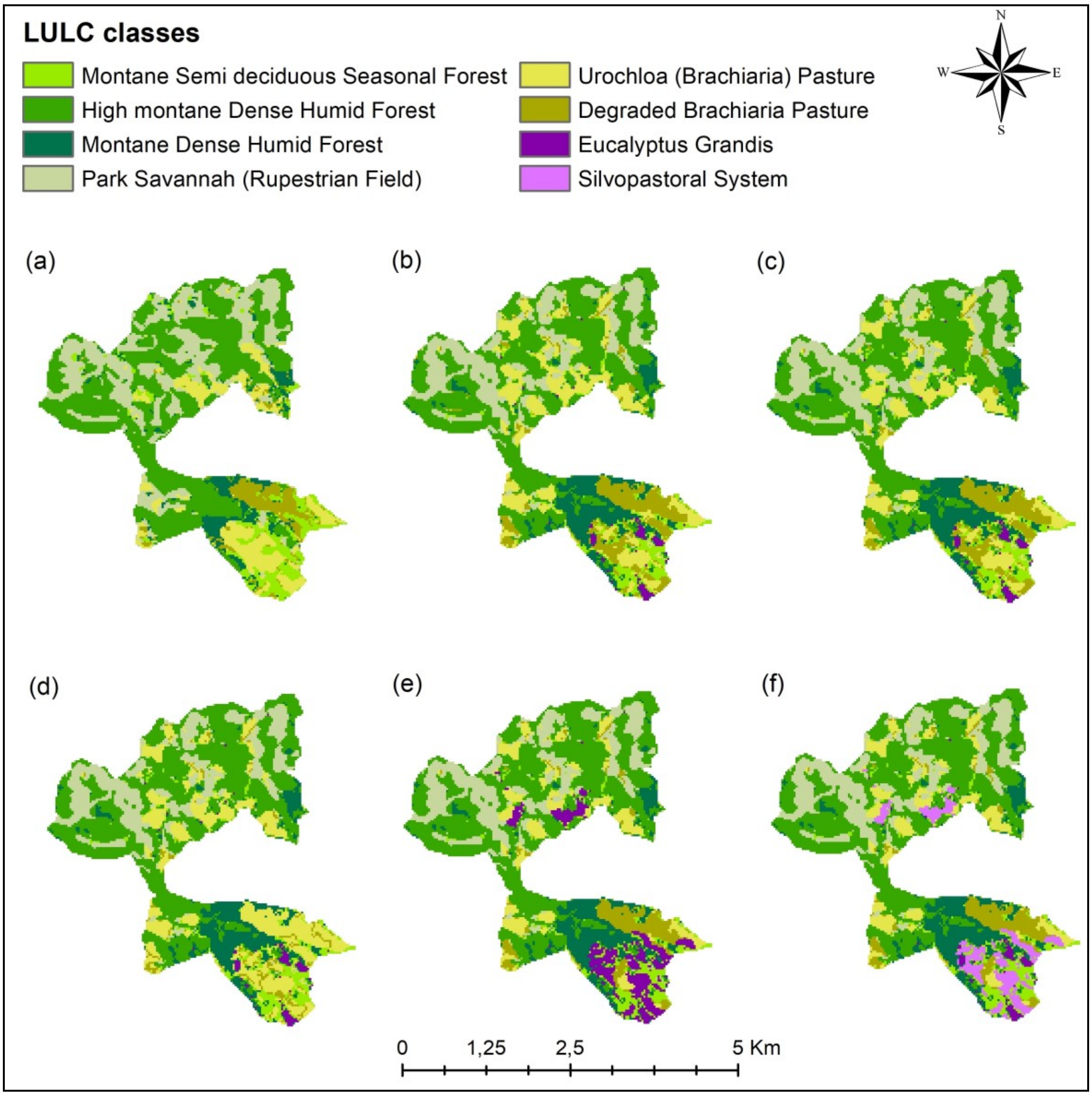

Figure 3.1 - LULC maps of the study area observed in 2007 (a) and 2017 (b) and scenarios predicted for 2027: Scenario 1 (c), Scenario 2 (d), Scenario 3 (e) and Scenario 4 (f).

Regarding the accuracy assessment, LULC maps generated for 2007 and 2017 presented an overall accuracy of 89.17% and 85.43%, respectively, indicating its appropriateness for the study. According to Thomlinson *et al.* (1999), an overall accuracy of 85% with no class less than 70% accurate is sufficient not to require mandatory reclassification or class aggregation. Softer criteria are also seen in similar studies (Foody, 2002). Based on the *Kappa* coefficient (Table 3.1), the resultant values of the supervised classification also demonstrated excellent performance for both maps (Landis and Koch, 1977). However, highest percentages of omission and commission errors were seen in classes Fm, Dm and Eu, as well as lowest percentages of accuracy in their mappings. According to Lu and Weng (2007), a remote sensing classification depends on several factors, such as the availability of a sufficient number of representative samples, geometric errors between images, high quality remotely detected images, the methods involved in the classification, just to name a few. Given these factors, there was a direct correlation between the lack of sufficient representative samples and the precision results of the previously mentioned classes. The number of samples used to classify each of these classes are less than the minimum of 50 samples recommended as a general rule (Banko, 1998).

LULC	LULC 2007					LULC 2017				
	Ref. Pts.	**Classes Acc.**	**Om. Error**	**Com. Error**	**Mapping Acc.**	**Ref. Pts.**	**Classes Acc.**	**Om. Error**	**Com. Error**	**Mapping Acc.**
Fm	29	79.3%	20.7%	17.9%	67.7%	18	78.3%	21.7%	35.7%	54.5%
Dl	164	93.3%	6.7%	3.8%	90.0%	187	86.6%	13.4%	5.1%	82.7%
Dm	18	72. 2%	27.8%	40.9%	48.2%	32	84.2%	15.8%	30.4%	61.5%
Sp	87	90.8%	9.2%	12.2%	80.6%	78	91.8%	8.2%	15.2%	78.8%
Pa	42	85.7%	14.3%	10.0%	78.3%	65	85.5%	14.5%	12.2%	76.5%
Pd	20	85.0%	15.0%	19.0%	70.8%	42	85.7%	14.3%	10.6%	77.8%
Eu	Ne.	Ne.	Ne.	Ne.	Ne.	7	100%	0%	30.0%	70.0%
	Overall accuracy: 89.17%					***Overall accuracy: 85.43%***				
	***Kappa coefficient*: 0.8480**					***Kappa coefficient*: 0.8248**				

Table 3.1 - Accuracy assessment results from observed LULC maps.
Notes: Ref. Pts. means the number of reference points (ground truth pixels) used for classification of each class.
Classes Acc. stands for the classes accuracy or classifier sensibility, which is obtained by dividing the total pixels correctly classified for each class in the reference data by the total pixels for that class in the reference data.
Om. Error means omission error or producer accuracy, which is calculated by dividing the total pixels not correctly classified for each class in the reference data by the total pixels for that class in the reference data/image.
Com. Error means commission error or user accuracy is calculated by dividing the number of pixels not correctly classified for each class in the classification by the total number of pixels for that class in the classification.
Mapping Acc. is the mapping accuracy for each class. It is stated as the number of correctly identified pixels within the total in the displayed area divided by that number plus error pixels of commission and omission.
Ne. means Nonexistent.

During the observed period (Figure 3.1 a, b and Figure 3.2) it is possible to note the advancement of brachiaria pastures (Pa) in the northern part of the study area, which represented an increase of 34.8% regarding its original area. The expansion of Pa caused a considerable impact to park savannah (Sp), being responsible for the suppression of 60.9 ha (23.3%) of the LULC class, and also affected the dense humid forests (Dl and Dm), with 6.21 ha loss (1.45%) (Table 3.2). The southern part of the study area revealed an increase of 35.82 ha (62.3%) of degraded pastures (Pd) and a significant reduction of 20.52 ha (27.3%) montane semideciduous seasonal forest (Fm). It was also possible to see the appearing of 12 ha of *eucalyptus grandis* (Eu) in areas previously occupied by pastures.

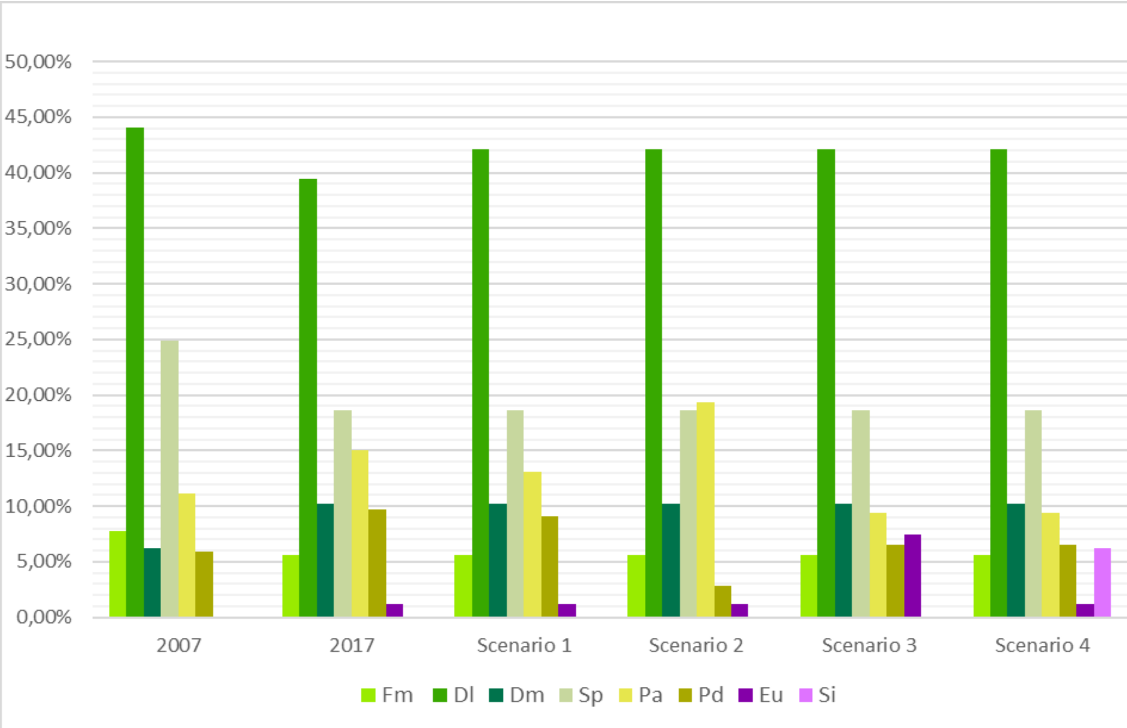

Figure 3.2 – Column chart showing distribution of LULC classes in percentage for each scenario in the study area. Notes: Fm stands for Montane Semideciduous Seasonal Forest; Dl is High montane Dense Humid Forest; Dm is Montane Dense Humid Forest; Sp is Park Savannah; Pa is *Urochloa* (Brachiaria) Pasture; Pd is Degraded Brachiaria Pasture; Eu is *Eucalyptus Grandis*, and Si is Silvopastoral system.

Regarding the projected future landscapes, the LULC map of scenario 1 (Figure 3.1 c) revealed an almost unnoticeable change in the study area, due to the spaced natural regeneration of 25.02 ha of Dl over the grasslands ends (Pa and Pd). However, scenario

2 (Figure 3.1d) clearly showed the reduction of Pd, largely due to the 40.86 ha recovery of degraded areas and the natural regeneration of 25.02 ha of Dl over its edges, remaining only 27.45 ha (2.84%) of degraded pastures. LULC maps of scenarios 3 and 4 also revealed visible landscape changes, arising from the 60.03 ha (500%) expansion of *eucalyptus grandis* in scenario 3 and the silvopastoral system implementation in scenario 4. Both implementations occurred to the detriment of 30 ha of Pd and 30 ha of Pa, located next to the 2017 eucalyptus forests, as well as the 25-ha natural regeneration of Dl over the brachiaria pasture borders (Table 3.2).

	Observed			**Simulation for 2027**							
	2007	**2017**		**Scenario 1**		**Scenario 2**		**Scenario 3**		**Scenario 4**	
LULC	Area (%)	Area (%)	Change (ha)	Area (%)	Change (ha)	Area (%)	Change (ha)	Area (%)	Change (ha)	Area (%)	Change (ha)
Fm	7.75	5.65	-20.52	5.65	0	5.65	0	5.65	0	5.65	0
Dl	44.06	39.48	-45.45	42.07	25.02	42.07	25.02	42.07	25.02	42.07	25.02
Dm	6.19	10.27	39.24	10.27	0	10.27	0	10.27	0	10.27	0
Sp	24.89	18.65	-60.93	18.65	0	18.65	0	18.65	0	18.65	0
Pa	11.18	15.06	37.26	15.06	-19.17	19.29	40.86	9.36	-55.08	9.36	-55.08
Pd	5.94	9.66	35.82	9.66	-5.85	2.84	-65.88	6.56	-29.97	6.56	-29.97
Eu	0	1.24	11.97	1.24	0	1.24	0	7.45	60.03	1.24	0
Si	0	0	0	0	0	0	0	0	0	6.21	60.03

Table 3.2 - Percentage distribution of LULC classes in the study area in 2007, 2017 and four scenarios projected for 2027 and changes (in hectares) observed for each class between the analysis periods (2007-2017; 2017-2027).

3.2 CARBON CAPTURE AND STORAGE SPATIAL DISTRIBUTION MAPS

During data processing, InVEST creates intermediate results that map carbon stocks separately by carbon compartment (AGB or C above, BGB or C below, SOC or C soil and DOM or C dead) and by time (current and / or future). Based on these 8 intermediate raster maps, InVEST produces two LULC scenarios (current and future) in the same spatial resolution of the input maps (30m) used to run the model and creates a log file with the simulation parameters. As output, InVEST generates four raster maps that display the amount of carbon stored in each LULC class, for the current and future scenarios, the carbon sequestered in this period (for the calculation of the difference between future and current scenario) and the net present value, representing gains (sequestration) or losses (emissions) for each unit area (pixel) of the map. InVEST also creates an HTML page to consolidate the results of carbon storage (current and future), carbon sequestration and its economic valuation at net present value. The LULC maps generated by the InVEST carbon module for each scenario were organized into two general carbon storage and sequestration maps to aid visual interpretation and comparison of their results over time (Figures 3.3 and 3.4).

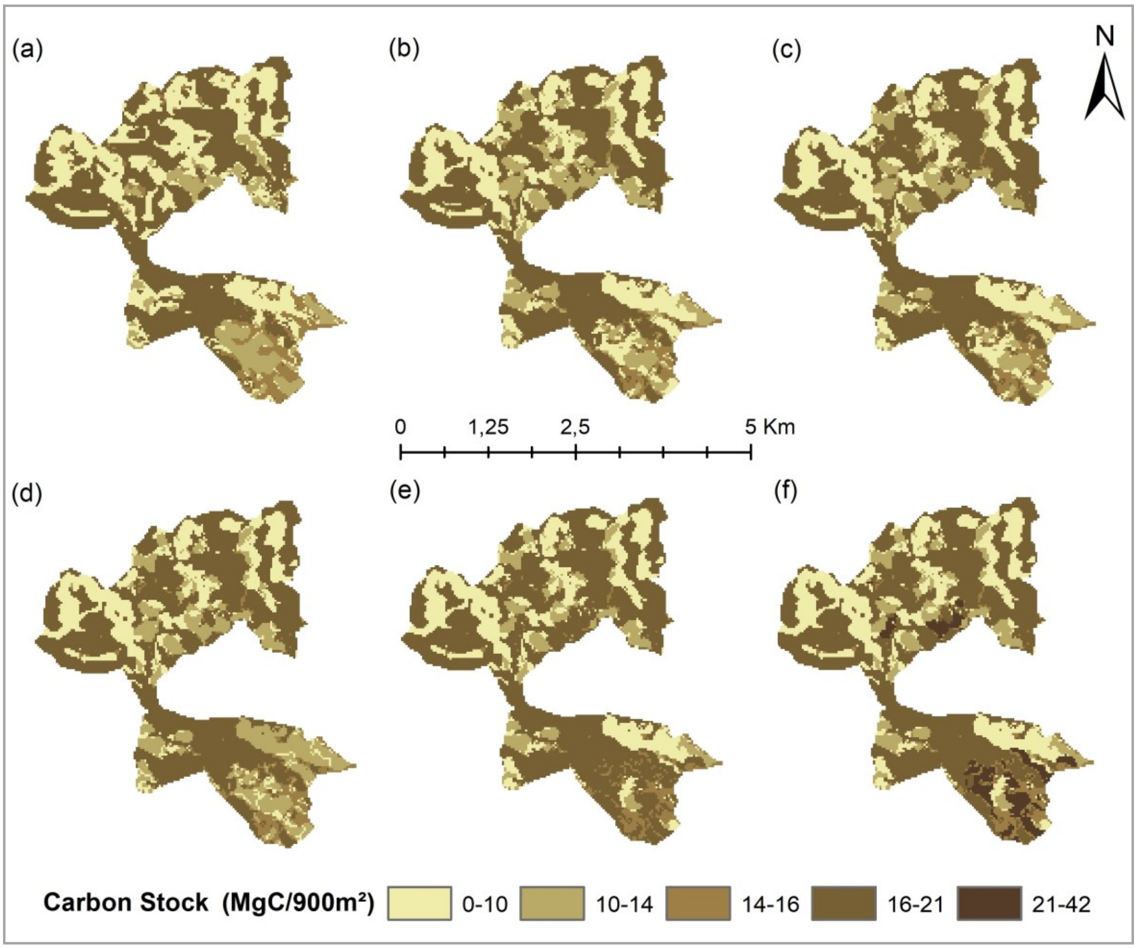

Figure 3.3 – Study area carbon stocks (Mg C/900m²) in 2007 (a), 2017 (b), Scenario 1 (c), Scenario 2 (d), Scenario 3 (e) and Scenario 4 (f).

The spatial distribution of carbon storage and sequestration between 2007-2017 has shown higher levels of emissions on the northern side of the study area, where the advancement of brachiaria pastures impacted the high montane dense humid forest. On the southern side, lower emissions were observed on degraded pastures. It is also possible to observe throughout the study area that the higher levels of carbon storage are present in forested areas. Regarding the increase of carbon sequestration around the study area, replacement of park savannah by brachiaria pasture, growing of *eucalyptus grandis* over older pastures and natural regeneration of forests were the main factors that contributed to it.

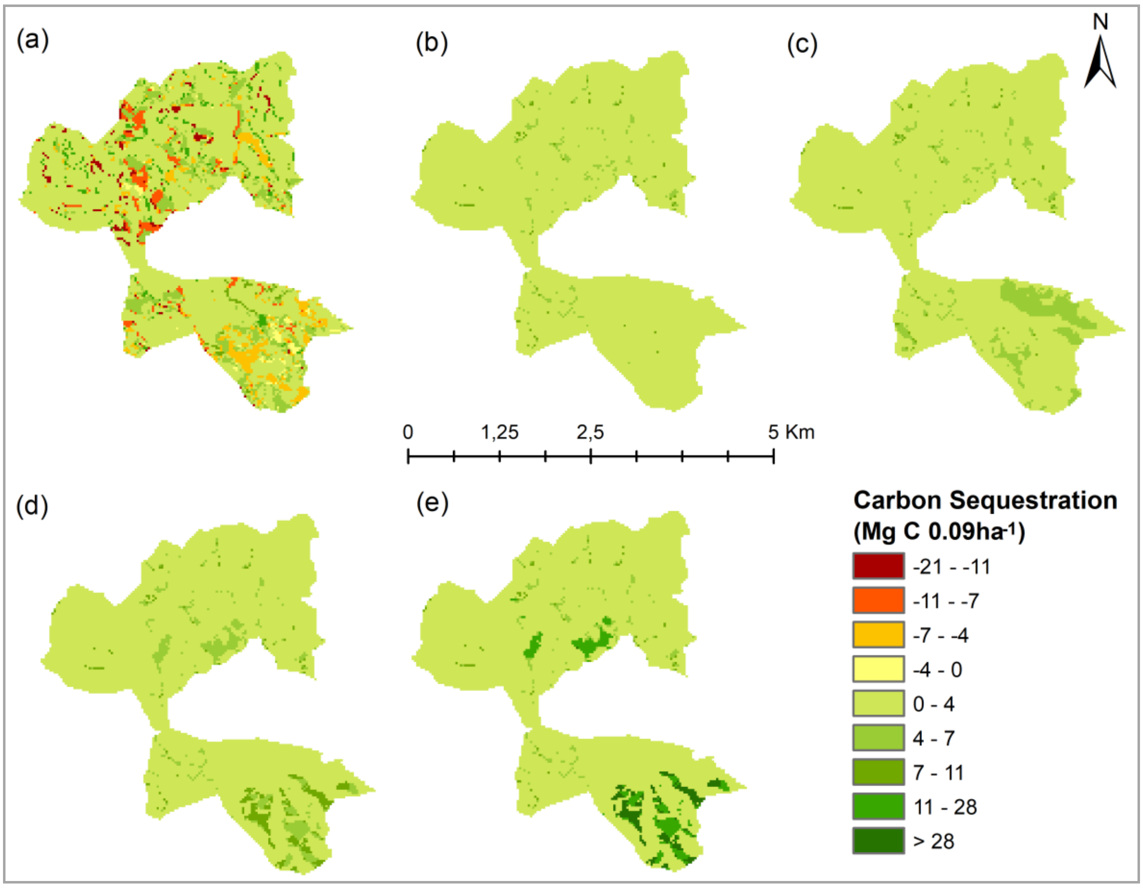

Figure 3.4 – Carbon sequestration and emission (Mg C/900m²) between 2007 and 2017 (a), and between 2017 and 2027 for scenarios one (b), two (c), three (d) and four (e).

During the 2017-2027 period, forest areas remained the highest carbon storage pools of the study area. The resultant carbon sequestration map of scenario 1 (Figure 3.4 b) highlighted where the natural forest regeneration occurred on landscape, due to its expansion over grassland ends. Similarly, in addition to indicating the landscape locations where carbon was captured, scenarios 2, 3 and 4 revealed their sequestration levels regarding the recovering of degraded pastures, the eucalyptus reforestation and silvopastoral system implementation, respectively.

Thus, it was possible to observe the future scenarios' contribution to the provision of climate-regulation ecosystem services, as well as the high potential of scenarios 3 and 4.

3.3 CARBON STORAGE AND SEQUESTRATION IN THE 2027 PREDICTED SCENARIOS

Future scenarios simulation (2027) has shown that all four alternatives would increase the total of carbon captured and stored in the study area when compared to 2017 (Figures 3.5 and 3.6). The overall distribution of carbon stored between pools followed the same patterns observed in 2007 and 2017 (Figure 3.5).

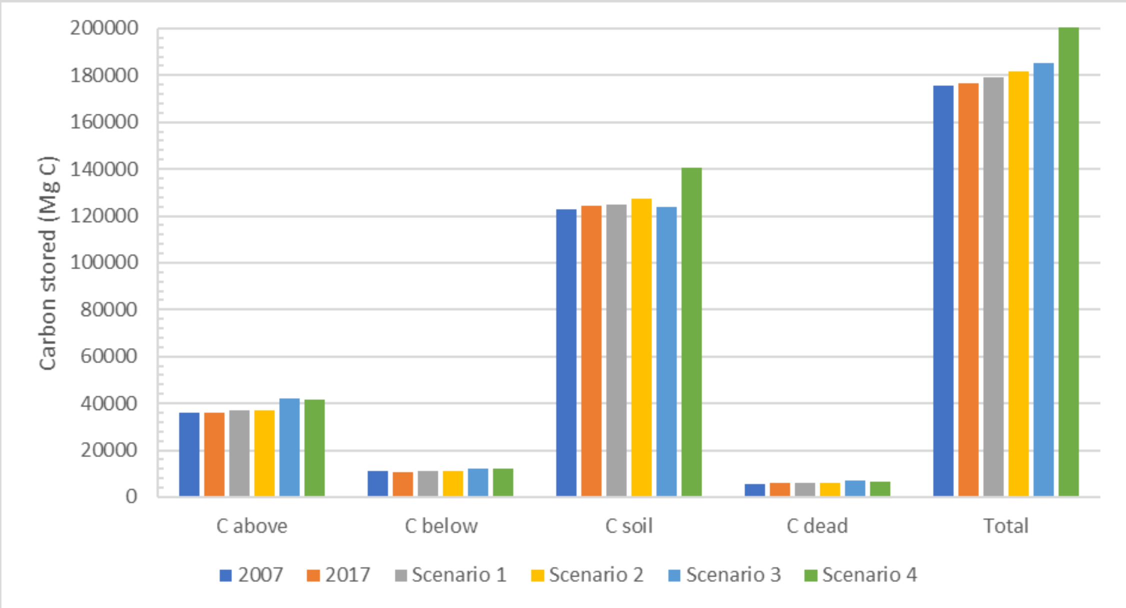

Figure 3.5 – Study area carbon stocks in observed and future scenarios.

Notably, carbon is mostly stored on soil, followed by the AGB, BG and DOM. Soil at 1-meter depth revealed to be the most important carbon pool in the landscape, being responsible for around 70% of all carbon stored in the landscape in all periods (Figure 3.5).

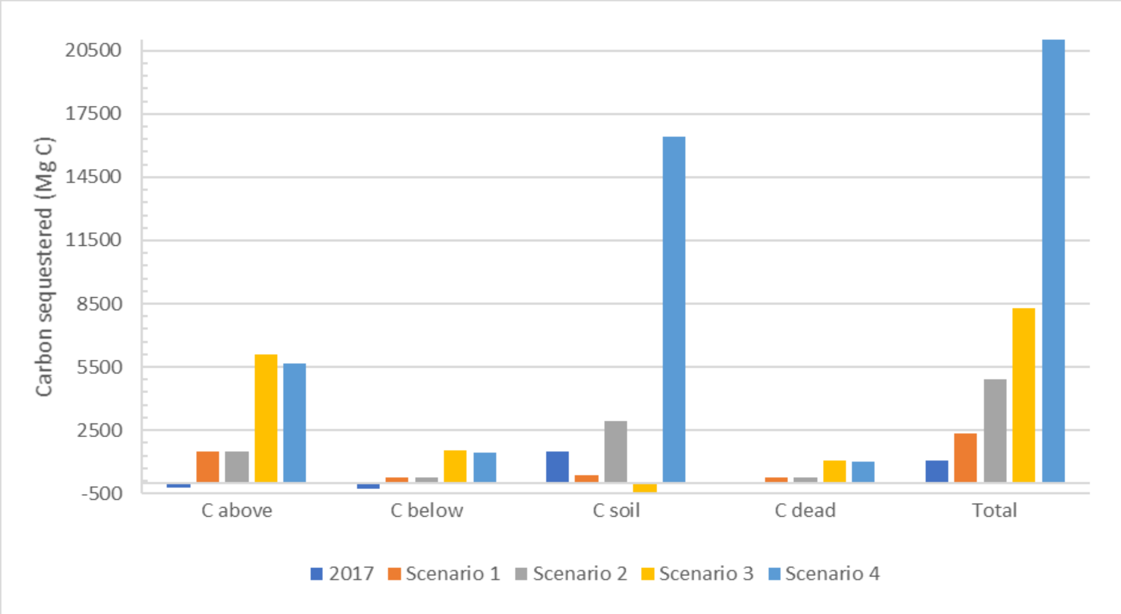

Figure 3.6 – Carbon sequestered in the study area of observed and future scenarios.

The soil compartment also showed the highest carbon densities in all scenarios (Table 3.3), showing values up to 2.3 times higher than the sum of the other carbon pools.

Date/Scenario	C above	C below	C soil	C dead	Total
2007	37.07	11.40	126.57	5.92	180.95
2017	36.86	11.09	128.09	5.99	182.03
Scenario 1	38.37	11.38	128.44	6.24	184.42
Scenario 2	38.37	11.38	131.09	6.24	187.08
Scenario 3	43.12	12.70	127.65	7.09	190.56
Scenario 4	42.70	12.57	144.97	7.01	207.26

Table 3.3 - Carbon density (Mg C ha^{-1}) in the study area of observed and future scenarios.

The natural regeneration of 25 ha of high montane dense humid forest (Dl) over grasslands (Pa and Pd), represented by scenario 1, would be enough to revert carbon emissions arising from forests loss in the 2007-2017 period and to capture a total of 2320 Mg C in the study area, around two times more than the total amount of carbon sequestered in 2017 (Figure 3.5), with a carbon sequestration rate of 0.24 Mg C ha^{-1} $year^{-1}$ (Figure 3.7). In scenario 2, the association of 25 ha natural regeneration of Dl over Pd areas with the 40 ha recovery of Pd would contribute to storing a total of 181,651 Mg C, capturing 4,897 Mg C (Figure 3.6) in the study area with a sequestration rate of 0.5 Mg C ha^{-1} $year^{-1}$ (Figure 3.7).

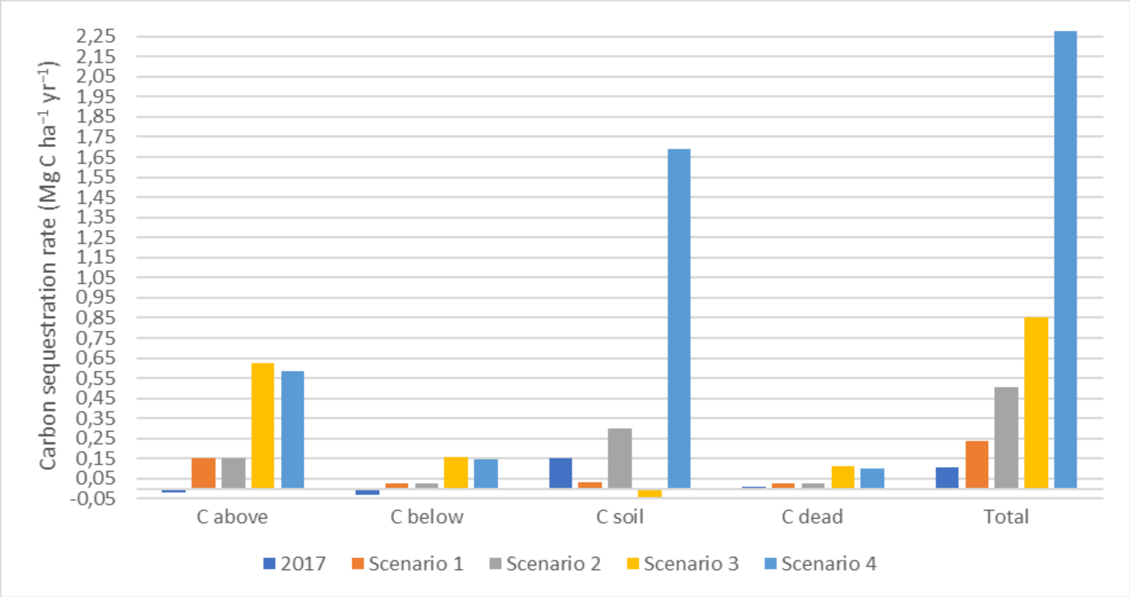

Figure 3.7 – Carbon sequestration rate in the study area in the observed and future scenarios.

The implementation of both eucalyptus (60 ha) reforestation and natural forest regeneration (25 ha) over the pastures edges, accordingly projected for the scenario 3, would significantly contribute to total carbon capture and storage in the study area, with 8,276 Mg C ha^{-1} and 185,030 Mg C respectively (Figures 3.5, 3.6 and Table 3.2). However, it revealed one of the lowest carbon densities of SOC (soil C), with 127.65 Mg C ha^{-1} (Table 3.2). It was also the only one to release carbon from this pool at a discrete emission rate of almost 0.05 Mg C ha^{-1} year^{-1} (Figure 3.7). Lastly, scenario 4 would provide the largest amounts of carbon storage and sequestration for the study area with 201,249 Mg C and 22,094 Mg C ha^{-1}, respectively. Its carbon sequestration rate was 2.27 Mg C ha^{-1} year^{-1}, 2.7 times greater than scenario 3. Based on these results, the combination of the silvopastoral implementation with the natural forest regeneration would be the best alternative to the provision of climate-regulation ecosystem services.

All future scenarios revealed higher carbon sequestration rates when analyzing their contribution only to the changed areas. In this case, scenario 2 revealed the lowest rate, with 7.43 Mg C ha^{-1} year^{-1}, followed by scenario 1 (9.27 Mg C ha^{-1} year^{-1}), scenario 3 (9.73 Mg C ha^{-1} year^{-1}) and scenario 4, with the highest rate of 28.8 Mg C ha^{-1} year^{-1}.

3.4 ECONOMIC VALUATION

Based on the inventoried forest data inserted in Sis Family software, we obtained the eucalyptus growth and yield forecasts simulations for each scenario, as well as the total wood volumes for energy and sawmill use according to DBH (diameter at breast height) classes (Table 3.4). These values made it possible to calculate the sale of standing timber at NPV and, subsequently, its consolidation in the economic opportunity table (Table 3.5).

All LULCC in the 2007-2027 period contributed to carbon sequestration in the study area, showing monetary values ranging from US$ 17,693.48 to US$ 365,262.68 on the voluntary carbon market (Table 3.5).

Source	Trees/ha	Average Diameter (cm)	Average Height (m)	Total Volume (m^3/ha)	Total for Energy (m^3/ha)	Total for Sawmill (m^3/ha)
SisEucalipto (Year 10)	1168	20.7	28.9	442.3	166.5	273.6
SisILPF (Year 10)	233	33.2	31.8	250.9	15.5	234.5

Table 3.4 – Estimates of eucalyptus growth and production in the tenth year, generated by the Sis family software, for scenarios 3 and 4.

The observed period (2007-2017) revealed the lowest monetary value and the lowest economic rates, when compared to the simulated period (2017-2027), which resulted in the indication of PES payment strategies as the best alternatives for that period. The PES strategies are also economically better than simulated scenarios in VM alternative, except in scenario 4 with PES - LEF. However, if we consider adding the economic opportunity of selling standing timber arising from the thinning of 40% of the trees, scenarios 3 and 4 would present significant monetary values of US$ 332,570.66 and US$ 521,669.79, respectively.

Considering the economic rates calculated for the study area, the PES - Forest would be the best payment strategy, reducing the farm's operating cost by 80%, regardless of the scenario analyzed. This cost reduction could be transformed into a profit of US$

12.25 ha^{-1} $year^{-1}$ and US$ 6.82 ha^{-1} $year^{-1}$ if the revenues from the selling of standing timber from scenarios 3 and 4 are computed.

Economic alternatives (NPV)	2007-2017	2017-2027			
	Observed	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total in 10 years					
Voluntary carbon market	17,693.48	34,595.82	73,024.60	123,404.78	365,262.68
PES - LEF	119,300.32	135,843.54	135,843.54	135,843.54	135,843.54
PES - Forest	353,834.57	370,377.79	370,377.79	370,377.79	370,377.79
Stand timber				209,165.88	156,407.51
Rate per study area					
Voluntary carbon market	1.82	3.56	7.52	12.71	37.62
PES - LEF	12.29	13.99	13.99	13.99	13.99
PES - Forest	36.44	38.14	38.14	38.14	38.14
Stand timber				21.54	16.11
Rate per changed area					
Voluntary carbon market	14.24 (124.29 ha)	138.27 (25.02 ha)	110.84 (65.88 ha)	145.10 (85.05 ha)	429.47 (85.05 ha)
PES - LEF	66.12 (180.43 ha)	66.12 (205.45 ha)	66.12 (205.45 ha)	66.12 (205.45 ha)	66.12 (205.45 ha)
PES - Forest	66.12 (535.14 ha)	66.12 (560.16 ha)	66.12 (560.16 ha)	66.12 (560.16 ha)	66.12 (560.16 ha)
Stand timber				245.93 (85.05 ha)	183.90 (85.05 ha)
Farm operating costs in 2017	- 47.43	- 47.43	- 47.43	- 47.43	- 47.43

Table 3.5 - Total economic income (US$) of each payment strategy, its rates (US$ ha^{-1} $year^{-1}$) under the study area (971 ha) and changed area perspectives; and farm operating costs in 2017 (US$ ha^{-1} $year^{-1}$).
Note: PES stands for payment for environmental services. LEF: legally exploitable forests. Forest: total preserved forest area. Values in parentheses refer to the area considered for each scenario or payment scheme.

The rates calculated for the changed area revealed that scenarios 1 (US$ 138.27 ha^{-1} $year^{-1}$), 3 (US$ 145.10 ha^{-1} $year^{-1}$) and 4 (US$ 429.47 ha^{-1} $year^{-1}$) have high potential to generate revenue from trading sequestered carbon in the voluntary market when compared to other scenarios or PES strategies.

The results also show the potential for combining the different payment schemes arising from sustainable scenarios. In this sense, scenarios 3 and 4 are great references for integrating all three alternatives. In an ideal arrangement, both scenarios could benefit from: the PES scheme implementation over the current native forest area; the trading of sequestered carbon in the voluntary market over the landscape change implemented by each scenario; and the selling of standing timber arising from the planned thinning of the trees.

4 DISCUSSION

4.1 CONTRIBUTING TO A CASE STUDY ON ES AT FARM LEVEL

The assessment of carbon storage and sequestration, both biophysically and economically, through the use of GIS and modeling tools technologies, are widely adopted by researchers in order to understand their impact to the provision of climate-regulation ecosystem services at broad and local scales (Arunyawat and Shrestha, 2018; Bagstad et al., 2013; Chaplin-Kramer et al., 2015; Levrel et al., 2017). This information, when analyzed under different scenarios perspective, is of great value to support the development of environmental policies and sustainable land use planning (Bottalico et al., 2016; Malczewski, 2006; Zawadzka et al., 2017). Considering that there are no local scale studies that analyze this subject from the point of view of a farm property, the understanding of how different LULCC scenarios can affect the provision of ecosystem services and contribute to economic opportunities to the sector will lead to the development of new local and regional scale studies, and will generate relevant information to the planning and management of sustainable farming.

4.2 CARBON STORAGE AND SEQUESTRATION ASSESSMENT

In this study, we carried out carbon dynamics assessments in a cattle ranch of Serra da Mantiqueira, Brazil, to understand the impacts and the economic opportunities from the provision of ecosystems services, based on four simulated future LULCC scenarios. Under a GIS approach, supported by the combined application of geoprocessing techniques (ArcGIS Desktop), ecosystem service modeling tools (InVEST Carbon model and InVEST scenario generator) and forest management simulators (SisEucalipto and SisILPF), we concluded scenario 4 as being the best alternative to be implemented in the study area, which provided the highest amounts of carbon capture and storage and showed the highest monetary results when considering its participation in different ecosystem services payment strategies. Scenario 4 was also the best alternative, considering its contribution to the total changed area.

The significant difference between scenario 4 and the other ones is due to the high amounts of SOC found at one-meter depth in silvopastoral systems, once the amount of 393.7 Mg C ha^{-1} found by Tonucci *et al.* (2011) was used in our study. When compared to other studies at the same soil depth, e.g. in a cambisol soil in two different silvopastoral systems of Costa Rica, with 132 and 183 Mg C ha^{-1} $year^{-1}$ (Amézquita et al., 2005); and in a latosol soil of an agroforestry system of *cocoa–gliricidia* in Indonesia with 160 Mg C ha^{-1} $year^{-1}$ (Smiley and Kroschel, 2008), we can infer that this disparity may have generated an overestimated result for this particular scenario. However, according to Ramachandran Nair *et al.* (2010), "estimates of C stored in agroforestry systems can range from 0.29 to 15.21 Mg C ha^{-1} $year^{-1}$ aboveground, and 30 to 300 Mg C ha^{-1} $year^{-1}$ up to 1-m depth in the soil", which leads us not to discard the actual carbon storage and sequestration potential of this scenario. Pandey (2002), in his study, appointed carbon sequestration rates in Indian agroforests varying from 19.56 Mg C ha^{-1} $year^{-1}$, in north Indian state of UP, to 23.46 – 47.36 Mg C ha^{-1} $year^{-1}$ in tree-bearing arid agroecosystems of Rajasthan, a value range that encompasses the sequestration rate found in scenario 4. Another fact that reinforces our result refers to a field research conducted by Simas (2002) in Serra Verde, an area located 8 km away from our study area. Simas (2002) found a total average SOC (C soil) stock of 344 Mg C ha^{-1}, which may indicate the potential for carbon storage and sequestration in the region soils.

The soil depth (1 meter) considered to this study, allied with the lack of methodologic patterns for soil sampling and C determination in different studies (Corazza et al., 1999; Da Silva et al., 2004; Zinn et al., 2002), makes comparing the scenarios results a difficult task. In addition, tree communities of Serra da Mantiqueira are characterized by high vegetation heterogeneity (Pompeu et al., 2014), which can affect local-scale results due to its specificities (e.g. climate, altitude, soil type, location, etc.). However, by way of comparison, Gatto *et al.* (2010) estimated that eucalyptus plantations in Minas Gerais can capture up to 13.63 Mg C ha^{-1} $year^{-1}$ from atmosphere, a value 48.7% higher than Scenario 3. Regarding natural forest regeneration, Feldpausch *et al.* (2004) estimated total C accrual of 7.04 Mg C ha^{-1} $year^{-1}$ in both aboveground and soil

(0-40cm) pools in a post-pasture tropical forest recovery of Central Amazonia, an amount 24% lower than scenario 1. Lastly, Trujillo, Fisher and Lal (2006) estimated that the input of soil organic carbon, under well-managed pastures of Brachiaria *dictyoneura* alone in the Eastern Plains of Colombia, is 10.3 Mg C ha^{-1} $year^{-1}$, which is 38.62% higher than scenario 2. However, according to Fisher (2007), soil carbon accumulation under introduced pastures in Brazil is substantial, but not enough to exceed half of the SOC values found on the eastern plains of Colombia. In this case, scenario 1 would be 44.27% higher than the maximum rate expected for Brazil.

4.3 MANAGING AND PLANNING SUSTAINABLE FARMING: SOME INSIGHTS

In general, all future LULCC scenarios shown to be benefic to the provision of climate-regulation ecosystem services. Our results revealed that a forest management approach mainly directed at natural or commercial reforestation (scenarios 1, 3 and 4) at the local provide better carbon sequestration rates over changed areas in comparison with the recovery of degraded areas (scenario 2). A forest management approach mainly geared towards maximizing economic incomes from wood production (scenario 3) reduces the carbon sequestration rate potential by approximately 66% compared to scenario 4.

Based on a new concept for sustainable meat called carbon neutral Brazilian beef, the study has also shown that the implementation of any of the analyzed future scenarios would be enough to neutralize ruminal methane emission of the cattle in the study area (Table 4.1).

Scenario	**Nelore on B. *brizantha*** (47.3 kg CH_4 $head^{-1}$ $year^{-1}$)	**Tier 1 IPCC** (56 kg CH_4 $head^{-1}$ $year^{-1}$)	**Tier 2 IPCC** (70 kg CH_4 $head^{-1}$ $year^{-1}$)
Scenario 1	0.7	0.6	0.5
Scenario 2	1.5	1.3	1
Scenario 3	2.6	2.2	1.8
Scenario 4	7	6	4.8

Table 4.1 – Amount of neutralized bovines (ha^{-1} $year^{-1}$) according to the carbon sequestration rate of each scenario (Mg C ha^{-1} $year^{-1}$) in the study area.

Notes: Nelore on B. *brizantha* means ruminal methane (CH_4) emission by Nelore beef steers, grazing on Brachiaria *brizantha* during the four seasons of the year (90 days/season), by average live weight of 375kg (Primavesi et al., 2014).

Value in parentheses shows the amount of annual methane emission from a bovine, used as a reference for CO_2e conversion.

A quantity of GHG can be expressed as CO_2e by multiplying the amount of GHG by its global warming potential (GWP). The GWP of CH_4 is 25 (Eckaus, 1992).

A quantity of C can also be expressed as CO2e by dividing the amount of C by its conversion factor 0.2727, calculated by the relationship between the molecular weight of carbon dioxide and carbon (44/12) (Spellman, 2015).

Concerning the economic assessment, the decision on which payment scenario and strategy to implement should be supported by prior analysis of the payment schedule, as well as the revision of its initial investment costs. For example, PES schemes generally used to pay immediately after its implementation, which does not occur in VM and selling standing timber. In scenarios 3 and 4, the potential economic opportunities arising from their implementation demand an initial investment of US$ 662.06 ha^{-1} and US$ 484.21 ha^{-1} respectively, as to their maintenance and planting costs. The introduction of eucalyptus trees in livestock and agricultural production systems is an interesting alternative for diversification and income increase, contributing to the balance of GHG from livestock activity and adding value to production.

The evidence of the importance of future LULC changes to the provision of climate-regulation ecosystem services, as well as their potential monetary value related to the implementation of different sustainable scenarios and the choice of different payment strategies, can be relevant to support decision-making regarding planning and management in this and other similar farming landscapes.

4.4 LIMITATIONS AND SIMPLIFICATIONS

During the study period, we faced some difficulties that led us to discuss some limitations and simplifications found, as well as workarounds and impacts on results. The first limitation we found is related to the spatial and temporal resolution of the images chosen for LULC mapping and the images chosen for mapping validation.

During the creation of LULC maps, the use of high spatial resolution images (30 m) from LANDSAT 5 and 8 satellites was not enough to prevent overlap of certain LULC classes. On the 2017 LULC map, part of montane semideciduous seasonal forest (Fm), located at the extreme south of the study area, was overlaid by the eucalyptus forest planted next to Fm in 2007 due to the height of its crowns that hid the original forest, giving a false idea of change and impacting the Fm loss result during 2007-2017 period, as well as the carbon storage and sequestration values calculated for this forest fragment.

The temporal resolution may also be considered as a potential limitation on studies requiring VHR satellite images of past periods. In our study, we used these images to support the creation of training samples related to the supervised map classification and to perform its validation. However, we did not find VHR images taken in 2007. As a workaround, we used an image taken in 2008 and asked farm owners to point out any changes in the landscape during the time frame that was not recorded by the image.

The resultant LULC maps of 2007 and 2017 also revealed a meaningful change related to the classification of Dl and Dm, in the altitude zone that defines the transition area of these two classes (Figure 3.1). The class Dm gained 39 ha at the expense of the class Dl. Although the change did not impact the results of this study, since we used carbon pools data of dense humid forest for both classes, it could change the results in similar studies. According to Helmer *et al.* (2000), in tropical mountain regions, different illumination angles may obscure the differences between the spectral responses of forests and consequently affect LULC mapping with satellite imagery.

Although InVEST plays an important role to perform this study, limitations and simplifications are also present in the different models available (Sharp et al., 2016), which makes it relevant for users to consider them carefully, investigating the possible consequences in their specific analysis. These limitations and simplifications are explained in InVEST's user guide and may be consulted according to the model used.

In our study, we observed some simplifications related to carbon pools, such as the SOC. The absence of a procedure or standard for data gathering may confuse the model parameters insertion. For example, the SOC may vary according to the depth analyzed. We considered carbon in the 100 cm of soil depth because studies of carbon spatial variability have shown deep carbon incorporation in pastures under adequate management (Boddey et al., 2010; Fisher et al., 2007; Segnini et al., 2019).

Additionally, according to Beare et al., (2014), as cited in Lefèvre *et al.*, (2017), soils at greater depth have a higher capacity of storing additional carbon compared to topsoils because of a larger difference between the existing SOC content and the SOC saturation value. On the other hand, according to Ontl and Schulte (2012), main changes in SOC take longer times to occur, which should be taken into consideration when analyzing the results of this study.

In general, it can be stated that the amount of information for all carbon compartments is a difficulty that any user will face and may be aggravated if certain land uses and coverages have not been studied in relation to carbon. In our study, for example, we defined LULC forest classes (Fm, Dl, Dm and Sp) based on spatial data from the 2009 Minas Gerais forest inventory (IDE-Sisema, 2019). However, we did not find carbon stock information in the four carbon pools for the LULC Dl and Dm classes (High montane and Montane dense humid forest). Alternatively, we use the values provided by the national forest information system (SNIF, 2019) for the Dense Humid Forest class (more generic) in both mapped classes. Similarly, we did not find adequate values for three carbon pools (C above, C below and C dead) of *urochloa* pastures. Given the low relevance of these pools when compared to SOC, we chose to use the reference values of the InVEST model.

We also observed some limitations appointed by Sharp *et al.* (2016), where the InVEST model does not consider any factors affecting carbon storage dynamics other than the change of LULC class. Another carbon storage dynamics limitation is related to its static behavior in the model calculations, once the InVEST model does not consider trees decay processes to move carbon from one pool to another, as well its linear accumulation flows, ignoring the carbon sequestration dynamics over time.

4.5 GUIDELINES FOR FUTURE DEVELOPMENTS

Due to the SOC relevance to the obtained results in this study, a sensitivity analysis considering other soil depths (e.g. 0-40 cm and 0-60cm), as well as its carbon change dynamics over time, would help us to understand how this carbon pool impacts the overall results. In the same sense, we did not consider the impacts of spatial variability on carbon stocks change within the same forest. According to some authors (Amézquita et al., 2005; Caldeira et al., 2015; Parron et al., 2015a), the amount of carbon stored in a forest is directly related to characteristics like topography, age, altitude and its successional stage, aspects not addressed by this study in depth. The accuracy of results can be improved when more detailed carbon stock data are available and updated for all carbon pools and LULC classes in Serra da Mantiqueira. Future studies will include LULC mappings from VHR satellite images and the development of specific LULC classes based on carbon-storage dynamics factors (e.g. altitude, topography, age, successional stage, soil, among others).

5 CONCLUSION

This exploratory and awareness-raising study assessed the provision of climate-regulation ecosystem service, in both biophysics and economic aspects, through the analysis of the carbon storage and sequestration indicators at the landscape level as an outcome of LULCC observed between 2007 and 2017, and in four alternative scenarios for 2027 in a cattle ranch of Serra da Mantiqueira. The main objective of this study was to introduce and apply a GIS approach, supported by forest management and ecosystem services modeling tools, for spatial-temporal assessment of carbon, predict changes and estimate economic opportunities arising from the implementation of different sustainable scenarios in a farm property. The study also aimed to contribute to planning, decision-making and management processes for effective land use and sustainable forest management. The results found can be useful in management and planning for both environmental conservation policies and sustainable farming development. Since there are no studies biophysically and economically assessing the carbon capture and storage under the farm property perspective and objectives, the method presented in this study can help and foster new quantitative and economic assessments. The results also revealed that LULCC could have important impacts on carbon dynamics over time and space in the study area, where the decision about which scenario to implement can potentially provide significant immediate or long-term benefits.

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ANNEXES

ANNEX A – DATASET

Name	Type	Description / Source / Available at
Mapa de Áreas de Reserva Legal conforme Cadastro Ambiental Rural - CAR (Figure A.1)	CAD in PDF	Map of Legal Reserve Areas according to Rural Environmental Registry - CAR used in the extraction of layers relevant to the study. **Source:** Farm Owners **Available at:** Not publicly available
08JUN20131023-P2AS_R17C1-059275572010_01_P001 08JUN20131023-P2AS_R16C1-059275572010_01_P001 08JUN20131023-P2AS_R02C2-059275572010_01_P001 08JUN20131023-P2AS_R03C2-059275572010_01_P001	GeoTIFF	World View 01 VHR panchromatic images of the study area token in June 20, 2008 used to support the map classification and validation processes. **Source:** DigitalGlobe Foundation **Available at:** https://discover.digitalglobe.com/ (University partnership program)
17SEP12133046-M2AS_R02C1-059275572030_01_P001 17SEP12133046-M2AS_R02C2-059275572030_01_P001 17SEP12133046-M2AS_R03C1-059275572030_01_P001 17SEP12133046-M2AS_R03C2-059275572030_01_P001	GeoTIFF	World View 03 VHR multispectral images of the study area token in September 12, 2017 used to support the map classification and validation processes. **Source:** DigitalGlobe Foundation **Available at:** https://discover.digitalglobe.com/ (University partnership program)
LC08_L1TP_218075_20170905_20170917_01_T1	GeoTIFF	Landsat 8 OLI multispectral image of the study área token in September 5, 2017 used for classification of LULC 2017 map **Source:** USGS **Available at:** https://earthexplorer.usgs.gov
LT05_L1TP_218075_20070708_20161112_01_T1	GeoTIFF	Landsat 5 TM multispectral image of the study area token in July 8, 2007 used for classification of LULC 2007 map **Source:** USGS **Available at:** https://earthexplorer.usgs.gov
SF-23-Z-A	GeoTIFF	Arc Second SRTM Elevation (res. 90m) used to create the digital elevation model and the isolines of the study area **Source:** EMBRAPA Monitoramento por Satélite **Available at:** http://www.relevobr.cnpm.embrapa.br
1502_mg_mapa_solos_pol	Shapefile	Map of Soils of Minas Gerais used to gather information about the study area **Source:** IBGE **Available at:** http://200.198.57.191:8080/geoserver/ows?service=WFS&version=1.0.0&request=GetFeature&typeName=WebGis:1502_mg_mapa_solos_pol&outputFormat=SHAPE-ZIP
1601_mg_zonas_climaticas_pol	Shapefile	Minas Gerais climate zones used for climate analysis in the study area **Source:** IBGE **Available at:** http://200.198.57.191:8080/geoserver/ows

Name	Type	Description / Source / Available at
		?service=WFS&version=1.0.0&request=GetFeature&typeName=WebGis:1601_mg_zonas_climaticas_pol&outputFormat=SHAPE-ZIP
31MUE250GC_SIR	Shapefile	Districts of Minas Gerais in scale 1: 250,000 used in the presentation of the study area **Source:** IBGE **Available at:** https://www.ibge.gov.br/en/statistics/social/population/18890-meshes.html?=&t=sobre
Biomas_5000	Shapefile	Biomes of Brazil at scale 1: 50000,000 used to locate and identify the biome of the study area **Source**: IBGE **Available at:** http://www.geoservicos.ibge.gov.br/geoserver/wms?service=WFS&version=1.0.0&request=GetFeature&typeName=CREN:biomas_5000&outputFormat=SHAPEZIP
BRUFE250GC_SIR	Shapefile	Brazilian Federation Units in scale 1: 250,000 used in the presentation of the study area **Source:** IBGE **Available at:** https://www.ibge.gov.br/en/statistics/social/population/18890-meshes.html?=&t=sobre
invf_mapeamento_2009	Shapefile	Forest cover map of Minas Gerais in 2009 used for recognition and support for the definition of LULC classes in the study area **Source:** IBGE **Available at:** http://200.198.57.38/imagem/ief/invf_mapeamento_2009.zip
Koppen_Brazil_2013	Shapefile	Köppen climate classification (refined by ALVARES et al 2013) in high resolution only for Brazil (IPEF) **Source:** IPEF **Available at:** http://www.ipef.br/geodatabase/repository/651da1d8va615cz1ad1da8s4rq8146a1dsa2132c1zn1/Koppen_Brazil_2013.rar
lim_pais_a	Shapefile	Country limits used in the presentation of the study area **Source:** IBGE **Available at:** https://www.ibge.gov.br/en/statistics/social/population/18890-meshes.html?=&t=sobre
Mapa de Solos de Minas Gerais	Shapefile	Map of Soils of Minas Gerais used to gather information about the study area **Source:** IDE-Sisema **Available at:** http://idesisema.meioambiente.mg.gov.br/

Table A.1 – External dataset used in the case study.

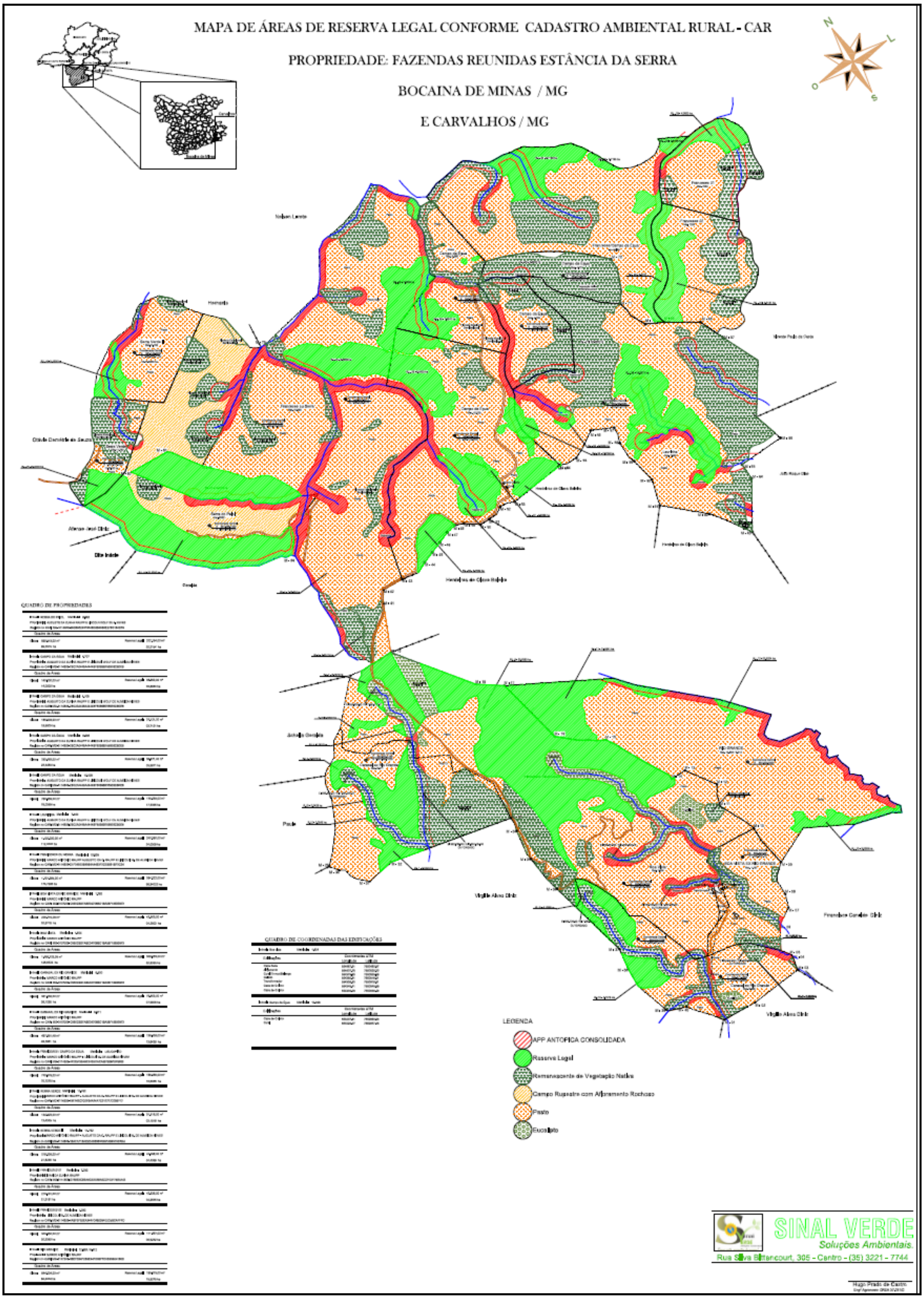


Figure A.1 – Rural Environmental Register (CAR – Cadastro Ambiental Rural) used to extract the shapefiles for the development of the study.

ANNEX B – RESEARCH FLOWCHARTS

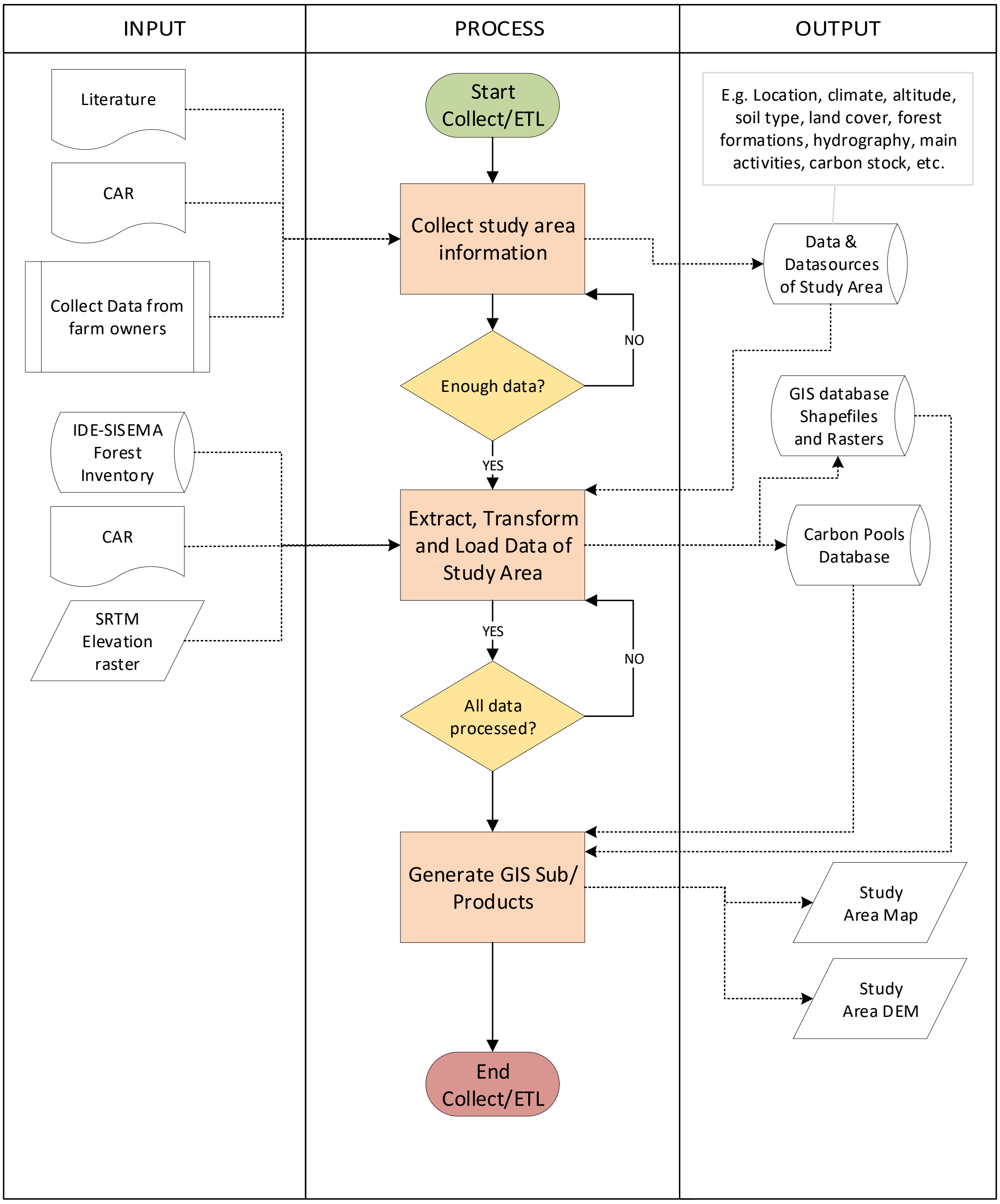


Figure B.1 – Flowchart of "Research and Collect Data of Study Area" and "Extract, Transform and Load Data of Study Area" processes with their main inputs and outputs.

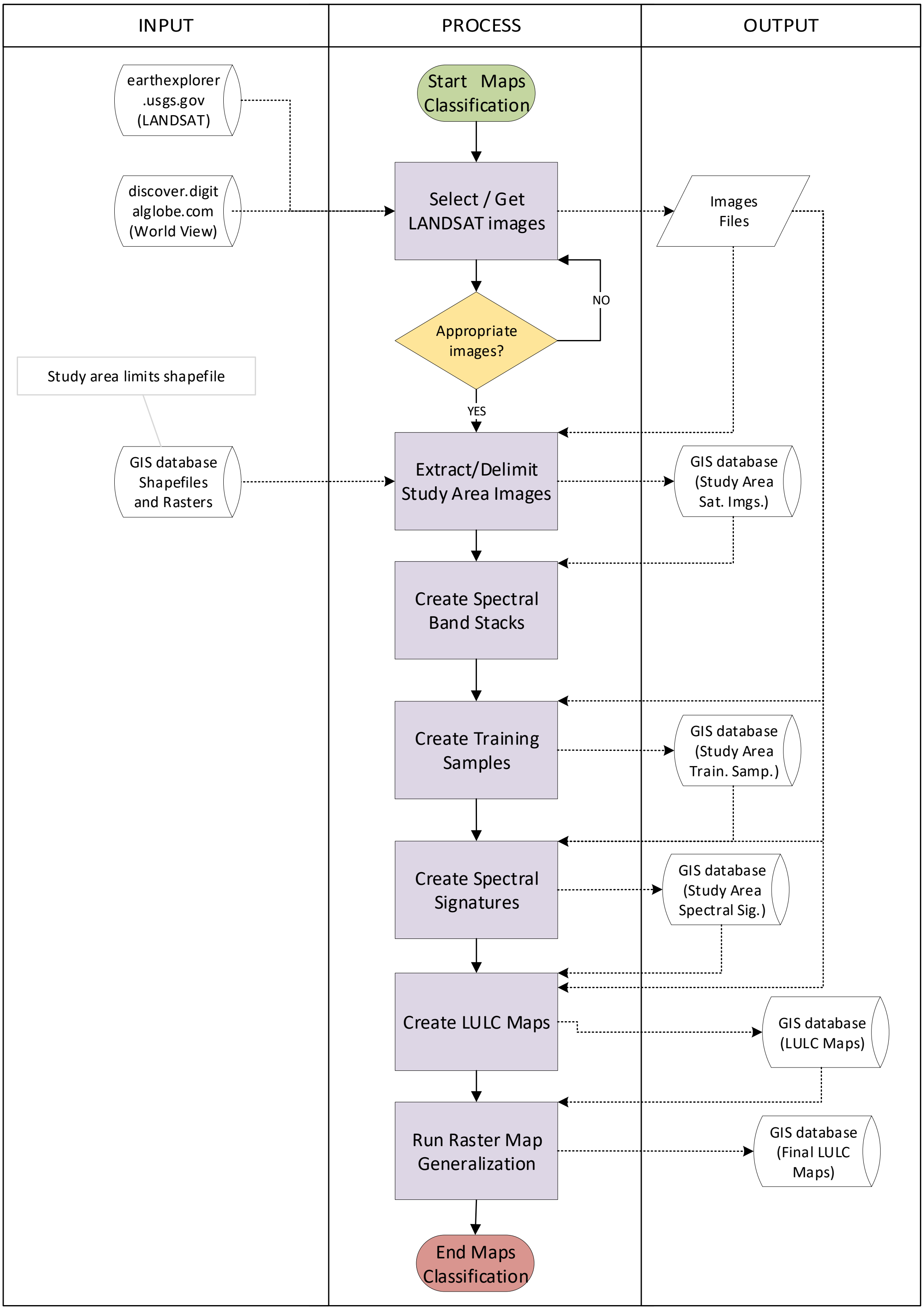


Figure B.2 – Flowchart of "Perform Maps Classification" process with its main inputs and outputs.

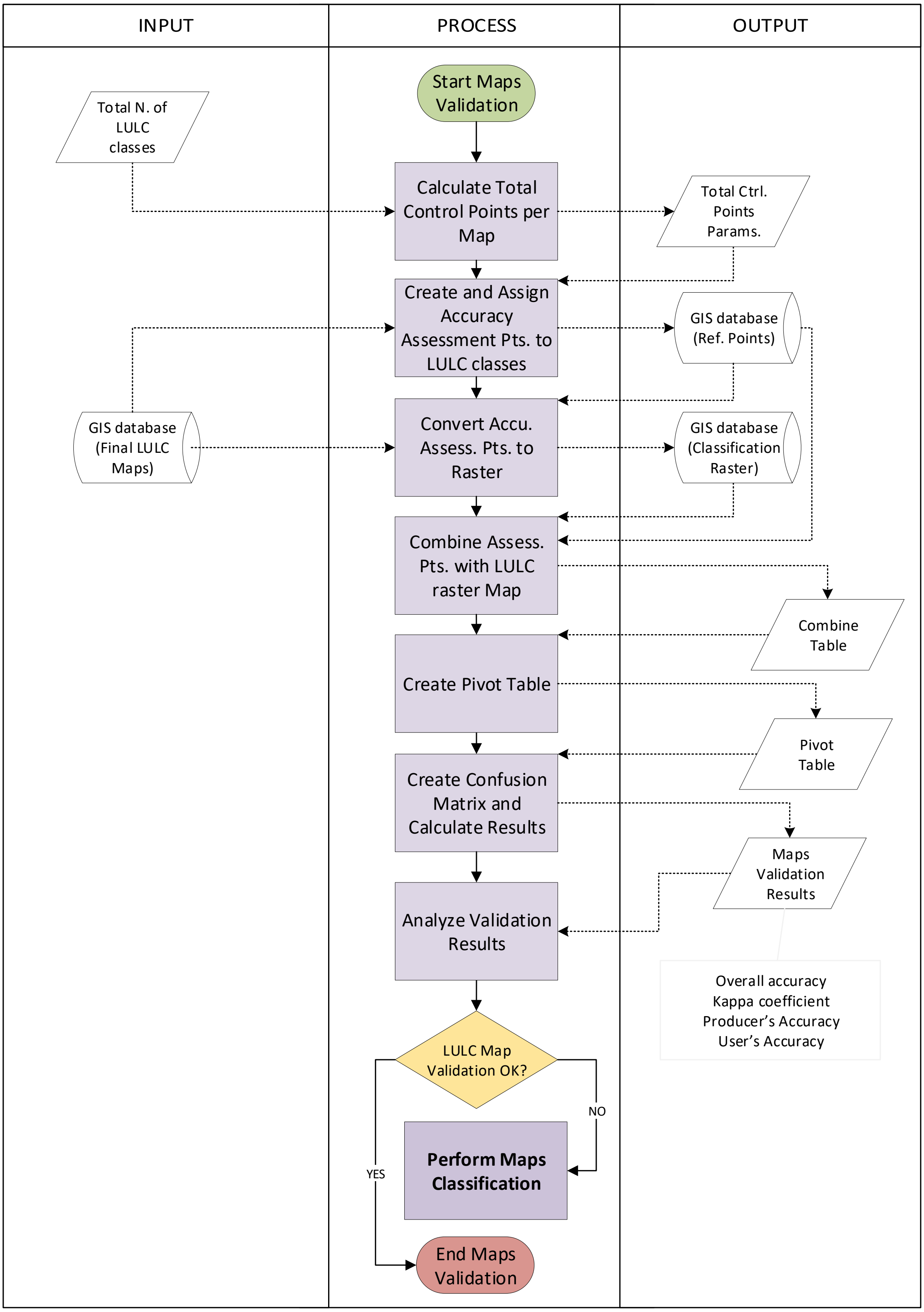


Figure B.3 – Flowchart of "Perform Maps Validation" process with its main inputs and outputs.

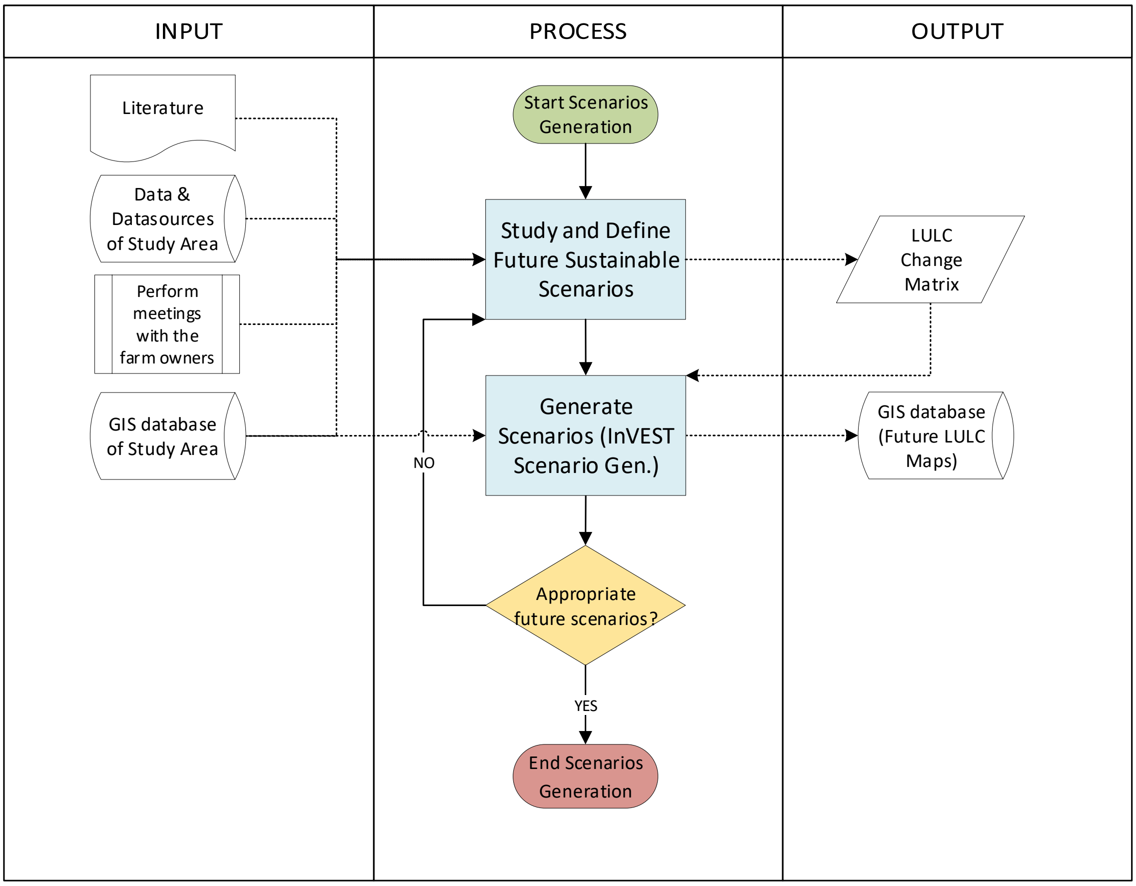


Figure B.4 – Flowchart of “Define Future Scenarios” and “Generate Future Scenarios” processes with their main inputs and outputs.

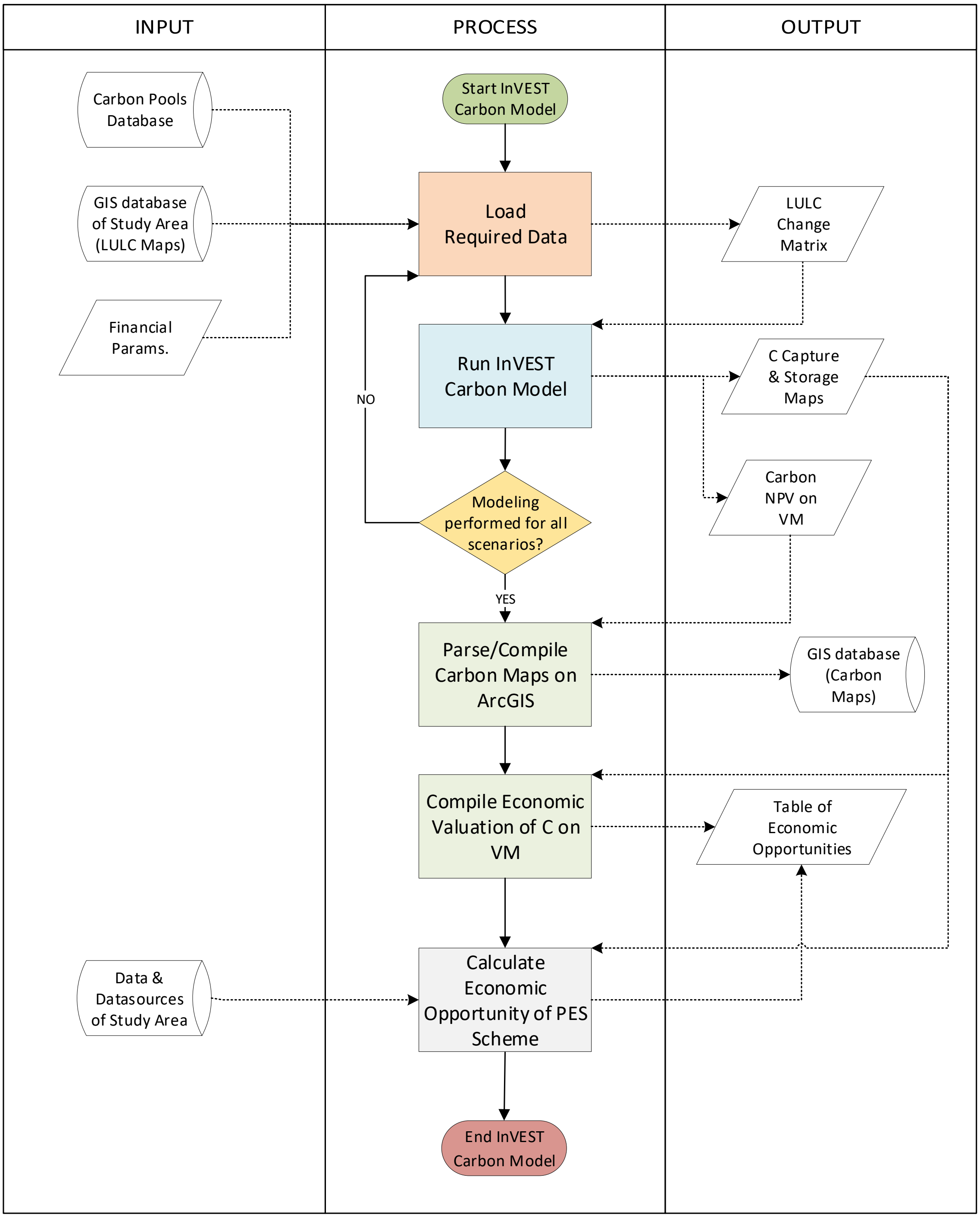


Figure B.5 – Flowchart of "Load Data of Carbon Pools & Economic Valuation", "Run InVEST Carbon Modeling Tool", "Compile Economic Valuation of C on VM", "Parse/Compile Carbon Maps" and "Calculate Economic Opportunity of PES Scheme" processes with their main inputs and outputs.

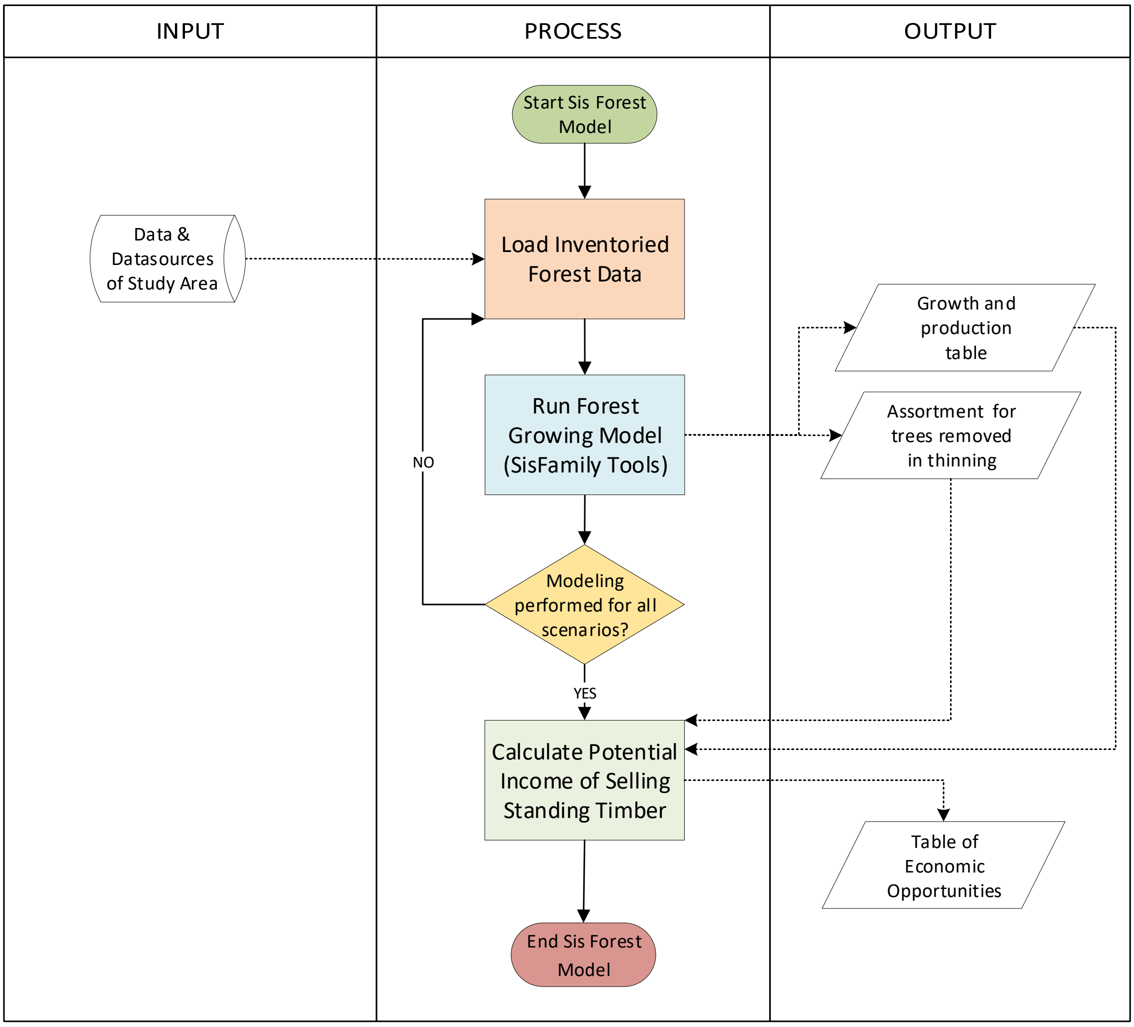


Figure B.6 – Flowchart of "Perform Forest Growing Model with Sis Family Tools" and "Calculate Potential Income of Selling Wood" processes with their main inputs and outputs.

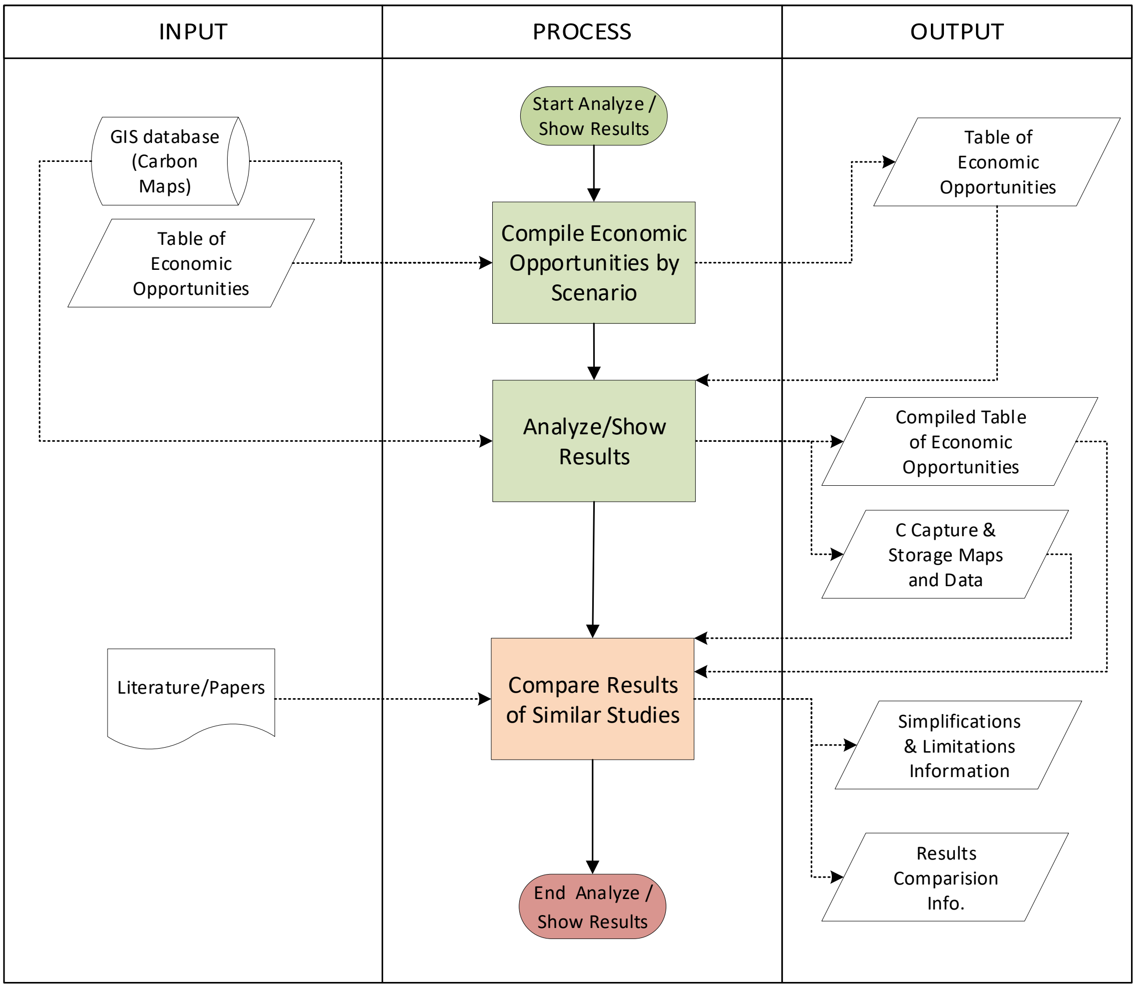


Figure B.7 – Flowchart of “Compile Economic Opportunities by Scenario”, “Analyze/Show Results” and “Compare Results of Similar Studies” processes with their main inputs and outputs.

ANNEX C – LULC MAPPING RESULTS

	Observed			Predicted (2027)							
	2007	2017		Scenario 1		Scenario 2		Scenario 3		Scenario 4	
LULC	Area	Area	Change	Area	Change	Area	Change	Area	Change	Area	Change
Fm	75.06	54.54	-20.52	54.54	0	54.54	0	54.54	0	54.54	0
Dl	426.87	381.42	-45.45	406.44	25.02	406.44	25.02	406.44	25.02	406.44	25.02
Dm	59.94	99.18	39.24	99.18	0	99.18	0	99.18	0	99.18	0
Sp	241.11	180.18	-60.93	180.18	0	180.18	0	180.18	0	180.18	0
Pa	108.27	145.53	37.26	126.36	-19.17	186.39	40.86	90.45	-55.08	90.45	-55.08
Pd	57.51	93.33	35.82	87.48	-5.85	27.45	-65.88	63.36	-29.97	63.36	-29.97
Eu	0	11.97	11.97	11.97	0	11.97	0	72	60.03	11.97	0
Si	0	0	0	0	0	0	0	0	0	60.03	60.03

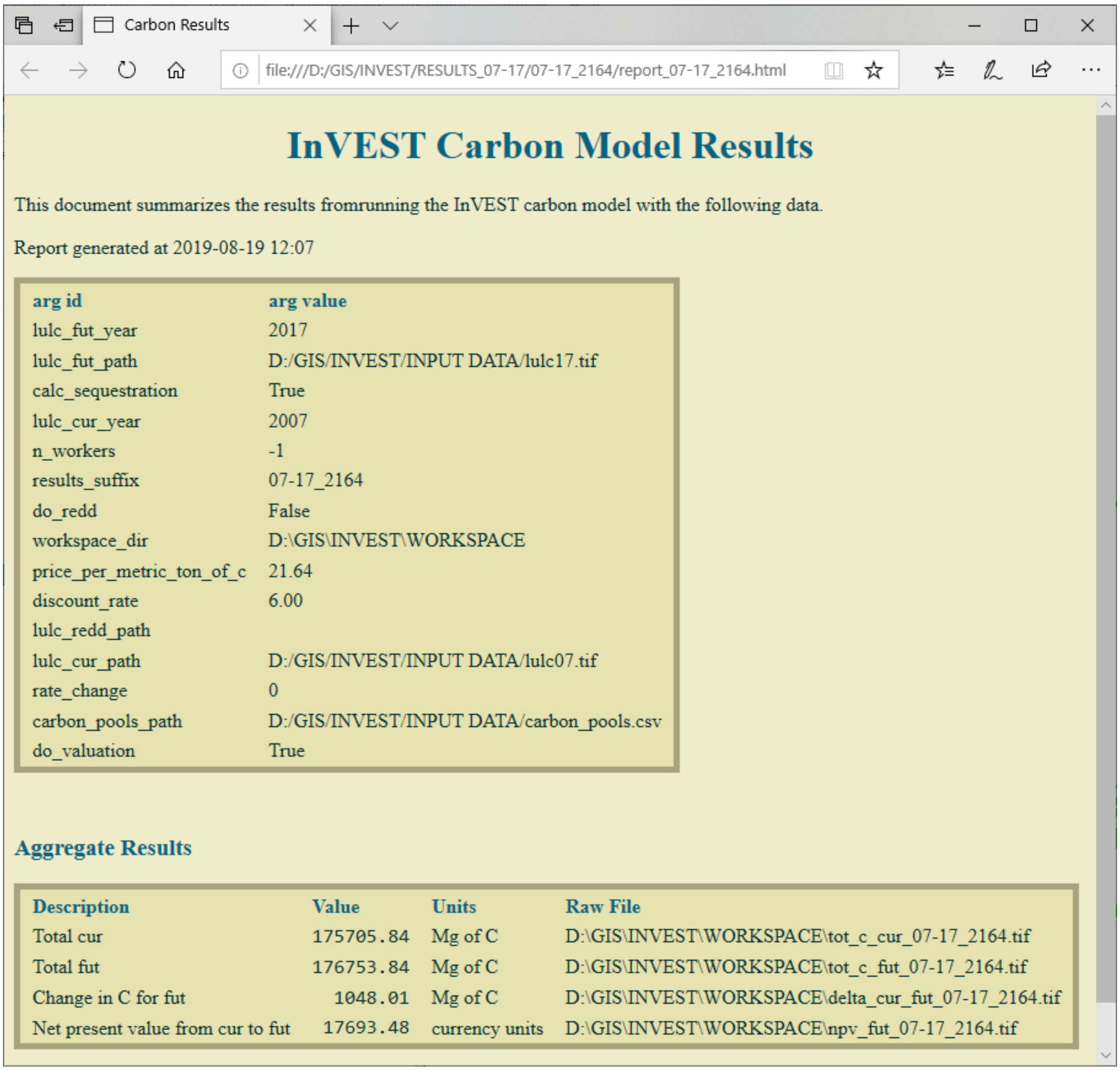
Table C.1 – Distribution of major LULC classes in the study area in 2007, 2017 and in four scenarios projected for 2027 and changes observed for each class between periods of analysis (2007–2017; 2017–2027).

ANNEX D – INVEST SCENARIO GENERATOR CONVERSION RESULTS

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
Basemap (30)	*LULC 2017 Map*		*Scenario 1 Map*		*Scenario 1 Map*		*Scenario 1 Map*	
LULC	**A.C. (ha)**	**P.C.**	**A.C. (ha)**	**P.C.**	**A.C. (ha)**	**P.C.**	**A.C. (ha)**	**P.C.**
Pa	19.17	213	0	0	35.91	399	35.91	399
Pd	5.85	65	60.03	667	24.12	268	24.12	268
Total	**25.02**	**278**	**60.03**	**667**	**60.03**	**667**	**60.03**	**667**

Table D.1 – LULC classes changed in each scenario generation relative to the provided basemap.
Notes: A.C. means area converted, P.C: number of pixels converted, Pa: brachiaria pasture, Pd: degraded brachiaria pasture. Value in parentheses refers to the basemap pixel size.

ANNEX E – INVEST CARBON MODEL RESULTS



InVEST Carbon Model Results

This document summarizes the results fromrunning the InVEST carbon model with the following data.

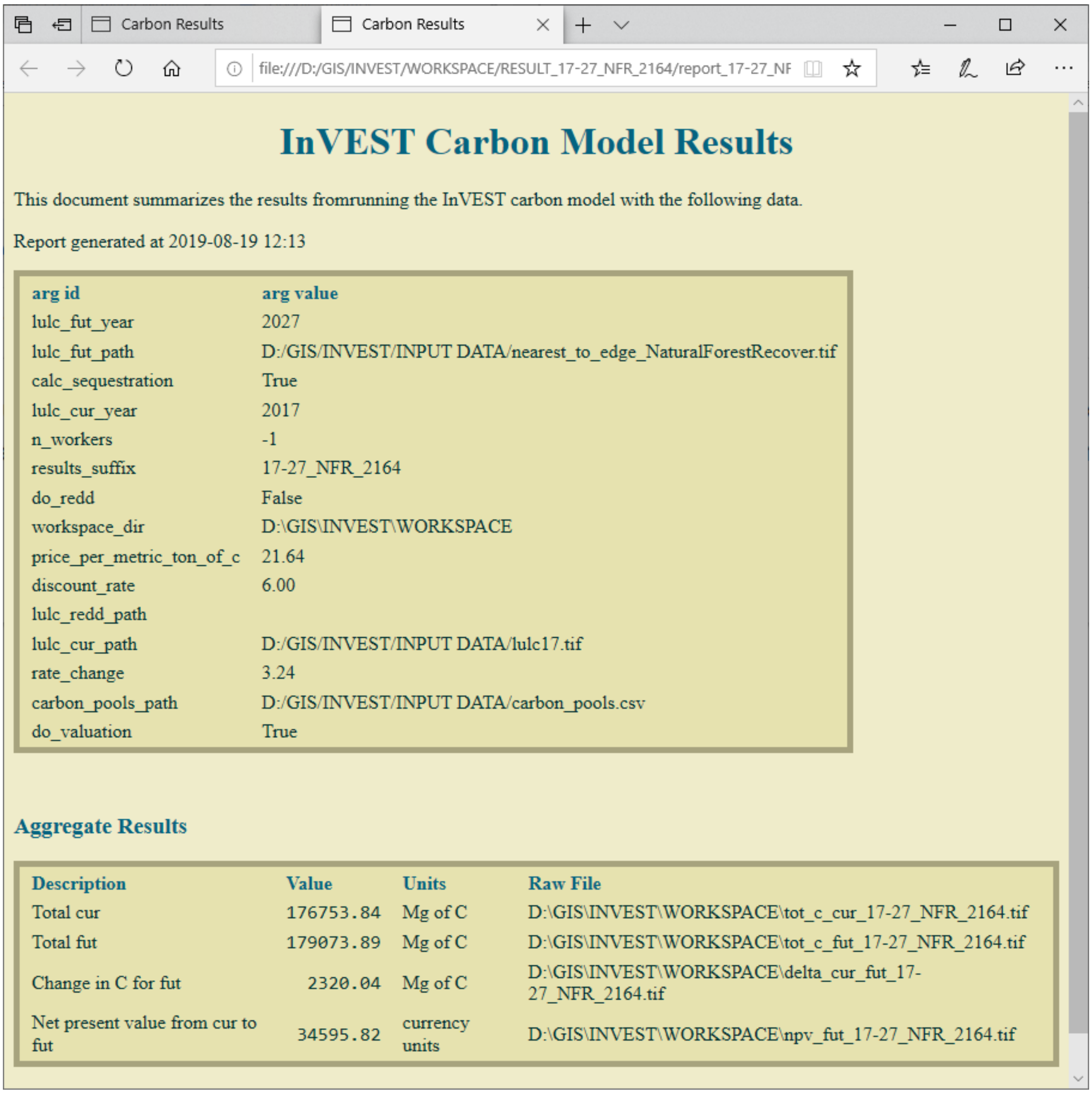
Report generated at 2019-08-19 12:07

arg id	arg value
lulc_fut_year	2017
lulc_fut_path	D:/GIS/INVEST/INPUT DATA/lulc17.tif
calc_sequestration	True
lulc_cur_year	2007
n_workers	-1
results_suffix	07-17_2164
do_redd	False
workspace_dir	D:\GIS\INVEST\WORKSPACE
price_per_metric_ton_of_c	21.64
discount_rate	6.00
lulc_redd_path	
lulc_cur_path	D:/GIS/INVEST/INPUT DATA/lulc07.tif
rate_change	0
carbon_pools_path	D:/GIS/INVEST/INPUT DATA/carbon_pools.csv
do_valuation	True

Aggregate Results

Description	Value	Units	Raw File
Total cur	175705.84	Mg of C	D:\GIS\INVEST\WORKSPACE\tot_c_cur_07-17_2164.tif
Total fut	176753.84	Mg of C	D:\GIS\INVEST\WORKSPACE\tot_c_fut_07-17_2164.tif
Change in C for fut	1048.01	Mg of C	D:\GIS\INVEST\WORKSPACE\delta_cur_fut_07-17_2164.tif
Net present value from cur to fut	17693.48	currency units	D:\GIS\INVEST\WORKSPACE\npv_fut_07-17_2164.tif

Figure E.1 – Summarized results of InVEST Carbon model execution for the observed scenarios (2007-2017).



InVEST Carbon Model Results

This document summarizes the results fromrunning the InVEST carbon model with the following data.

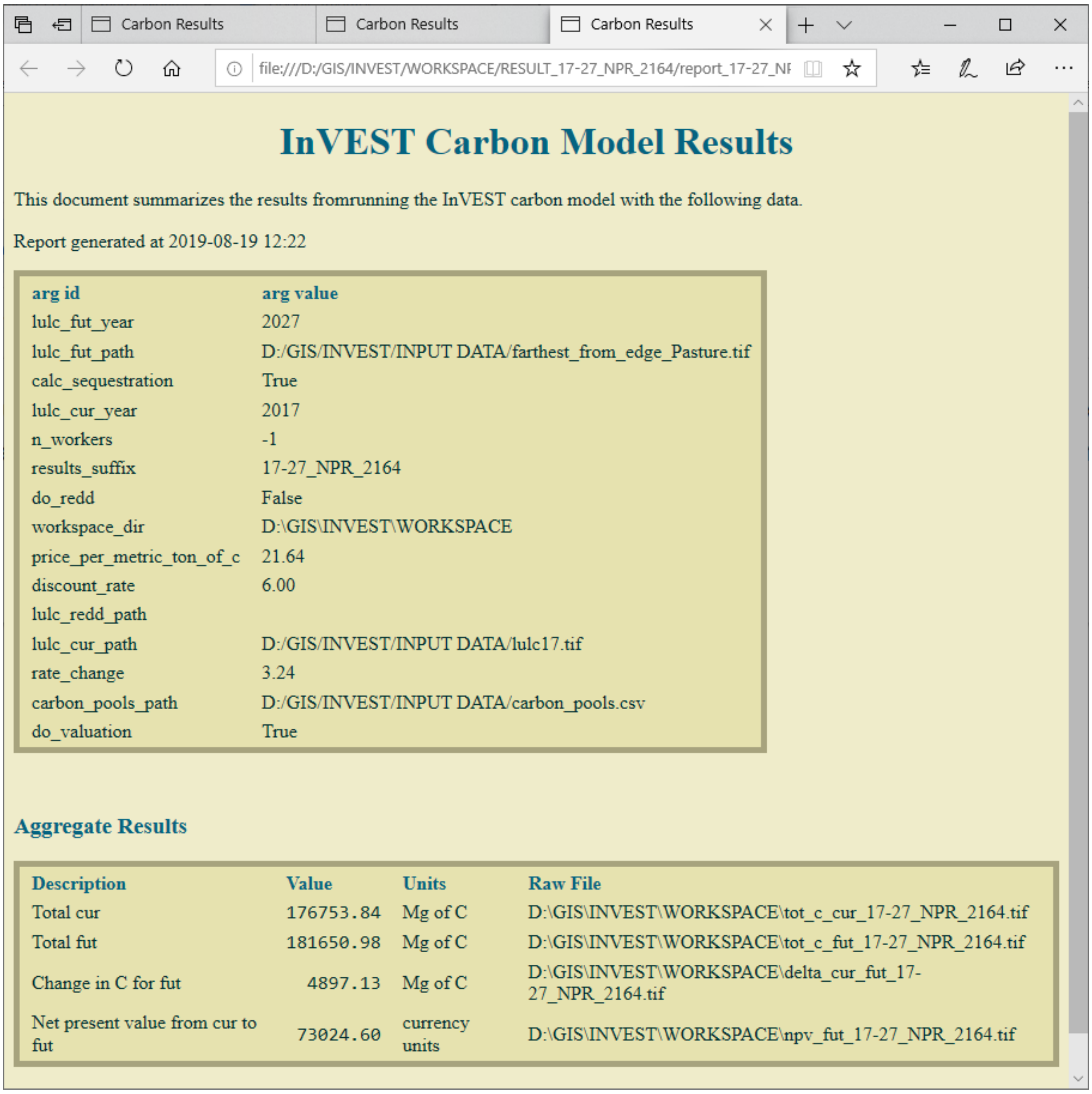
Report generated at 2019-08-19 12:13

arg id	arg value
lulc_fut_year	2027
lulc_fut_path	D:/GIS/INVEST/INPUT DATA/nearest_to_edge_NaturalForestRecover.tif
calc_sequestration	True
lulc_cur_year	2017
n_workers	-1
results_suffix	17-27_NFR_2164
do_redd	False
workspace_dir	D:\GIS\INVEST\WORKSPACE
price_per_metric_ton_of_c	21.64
discount_rate	6.00
lulc_redd_path	
lulc_cur_path	D:/GIS/INVEST/INPUT DATA/lulc17.tif
rate_change	3.24
carbon_pools_path	D:/GIS/INVEST/INPUT DATA/carbon_pools.csv
do_valuation	True

Aggregate Results

Description	Value	Units	Raw File
Total cur	176753.84	Mg of C	D:\GIS\INVEST\WORKSPACE\tot_c_cur_17-27_NFR_2164.tif
Total fut	179073.89	Mg of C	D:\GIS\INVEST\WORKSPACE\tot_c_fut_17-27_NFR_2164.tif
Change in C for fut	2320.04	Mg of C	D:\GIS\INVEST\WORKSPACE\delta_cur_fut_17-27_NFR_2164.tif
Net present value from cur to fut	34595.82	currency units	D:\GIS\INVEST\WORKSPACE\npv_fut_17-27_NFR_2164.tif

Figure E.2 – Summarized results of InVEST Carbon model execution for the observed scenario 1 (2017-2027).



Carbon Results | Carbon Results | Carbon Results

file:///D:/GIS/INVEST/WORKSPACE/RESULT_17-27_NPR_2164/report_17-27_NI

InVEST Carbon Model Results

This document summarizes the results fromrunning the InVEST carbon model with the following data.

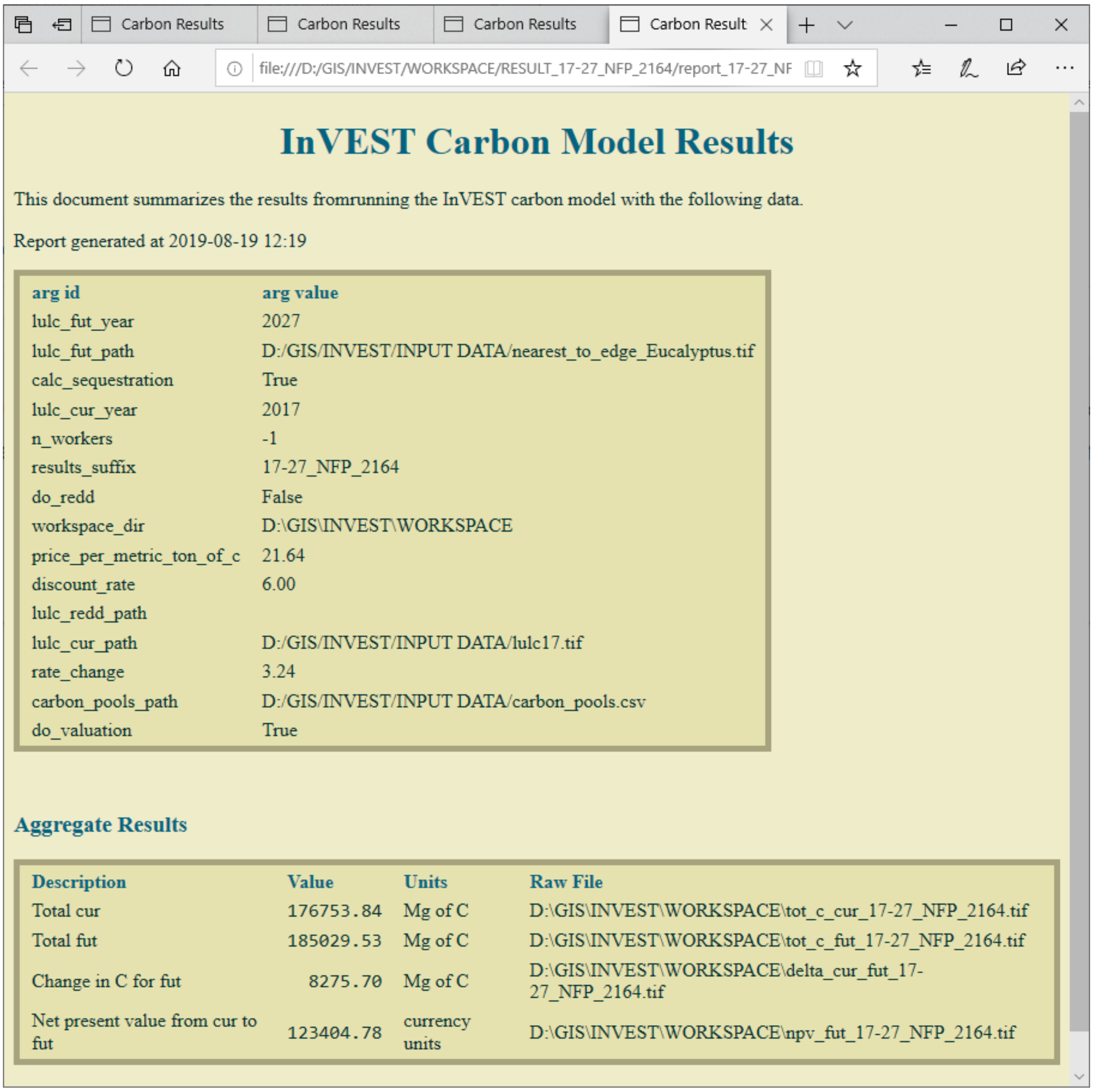
Report generated at 2019-08-19 12:22

arg id	arg value
lulc_fut_year	2027
lulc_fut_path	D:/GIS/INVEST/INPUT DATA/farthest_from_edge_Pasture.tif
calc_sequestration	True
lulc_cur_year	2017
n_workers	-1
results_suffix	17-27_NPR_2164
do_redd	False
workspace_dir	D:\GIS\INVEST\WORKSPACE
price_per_metric_ton_of_c	21.64
discount_rate	6.00
lulc_redd_path	
lulc_cur_path	D:/GIS/INVEST/INPUT DATA/lulc17.tif
rate_change	3.24
carbon_pools_path	D:/GIS/INVEST/INPUT DATA/carbon_pools.csv
do_valuation	True

Aggregate Results

Description	Value	Units	Raw File
Total cur	176753.84	Mg of C	D:\GIS\INVEST\WORKSPACE\tot_c_cur_17-27_NPR_2164.tif
Total fut	181650.98	Mg of C	D:\GIS\INVEST\WORKSPACE\tot_c_fut_17-27_NPR_2164.tif
Change in C for fut	4897.13	Mg of C	D:\GIS\INVEST\WORKSPACE\delta_cur_fut_17-27_NPR_2164.tif
Net present value from cur to fut	73024.60	currency units	D:\GIS\INVEST\WORKSPACE\npv_fut_17-27_NPR_2164.tif

Figure E.3 – Summarized results of InVEST Carbon model execution for the observed scenario 2 (2017-2027).



InVEST Carbon Model Results

This document summarizes the results fromrunning the InVEST carbon model with the following data.

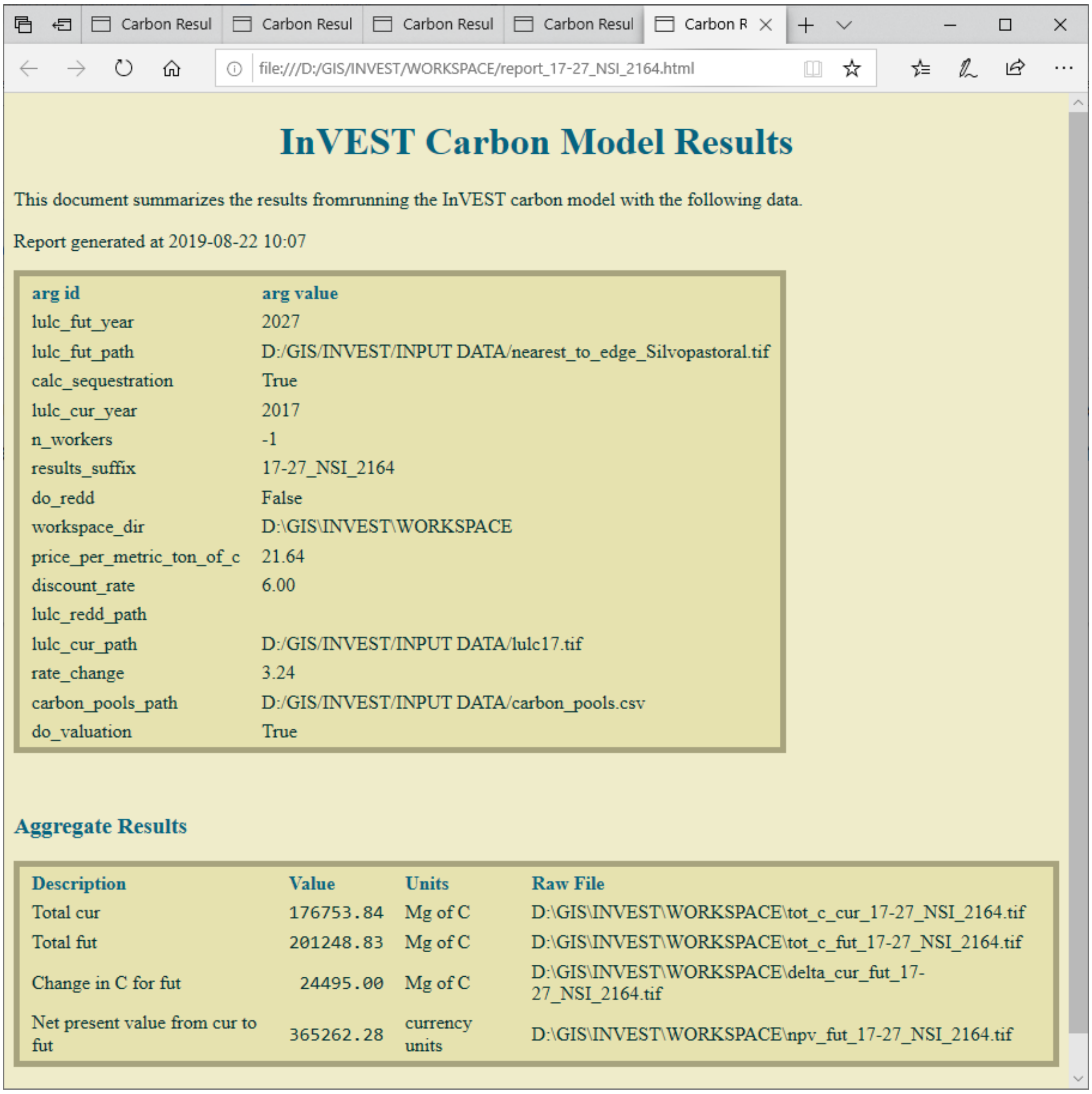
Report generated at 2019-08-19 12:19

arg id	arg value
lulc_fut_year	2027
lulc_fut_path	D:/GIS/INVEST/INPUT DATA/nearest_to_edge_Eucalyptus.tif
calc_sequestration	True
lulc_cur_year	2017
n_workers	-1
results_suffix	17-27_NFP_2164
do_redd	False
workspace_dir	D:\GIS\INVEST\WORKSPACE
price_per_metric_ton_of_c	21.64
discount_rate	6.00
lulc_redd_path	
lulc_cur_path	D:/GIS/INVEST/INPUT DATA/lulc17.tif
rate_change	3.24
carbon_pools_path	D:/GIS/INVEST/INPUT DATA/carbon_pools.csv
do_valuation	True

Aggregate Results

Description	Value	Units	Raw File
Total cur	176753.84	Mg of C	D:\GIS\INVEST\WORKSPACE\tot_c_cur_17-27_NFP_2164.tif
Total fut	185029.53	Mg of C	D:\GIS\INVEST\WORKSPACE\tot_c_fut_17-27_NFP_2164.tif
Change in C for fut	8275.70	Mg of C	D:\GIS\INVEST\WORKSPACE\delta_cur_fut_17-27_NFP_2164.tif
Net present value from cur to fut	123404.78	currency units	D:\GIS\INVEST\WORKSPACE\npv_fut_17-27_NFP_2164.tif

Figure E.4 – Summarized results of InVEST Carbon model execution for the observed scenario 3 (2017-2027).



Carbon Resul | Carbon Resul | Carbon Resul | Carbon Resul | Carbon R

file:///D:/GIS/INVEST/WORKSPACE/report_17-27_NSI_2164.html

InVEST Carbon Model Results

This document summarizes the results fromrunning the InVEST carbon model with the following data.

Report generated at 2019-08-22 10:07

arg id	arg value
lulc_fut_year	2027
lulc_fut_path	D:/GIS/INVEST/INPUT DATA/nearest_to_edge_Silvopastoral.tif
calc_sequestration	True
lulc_cur_year	2017
n_workers	-1
results_suffix	17-27_NSI_2164
do_redd	False
workspace_dir	D:\GIS\INVEST\WORKSPACE
price_per_metric_ton_of_c	21.64
discount_rate	6.00
lulc_redd_path	
lulc_cur_path	D:/GIS/INVEST/INPUT DATA/lulc17.tif
rate_change	3.24
carbon_pools_path	D:/GIS/INVEST/INPUT DATA/carbon_pools.csv
do_valuation	True

Aggregate Results

Description	Value	Units	Raw File
Total cur	176753.84	Mg of C	D:\GIS\INVEST\WORKSPACE\tot_c_cur_17-27_NSI_2164.tif
Total fut	201248.83	Mg of C	D:\GIS\INVEST\WORKSPACE\tot_c_fut_17-27_NSI_2164.tif
Change in C for fut	24495.00	Mg of C	D:\GIS\INVEST\WORKSPACE\delta_cur_fut_17-27_NSI_2164.tif
Net present value from cur to fut	365262.28	currency units	D:\GIS\INVEST\WORKSPACE\npv_fut_17-27_NSI_2164.tif

Figure E.5 – Summarized results of InVEST Carbon model execution for the observed scenario 4 (2017-2027).

ANNEX F – SISEUCALIPTO AND SISILPF OUTPUTS

SisEucalipto

TABELA DE CRESCIMENTO E PRODUÇÃO - Eucalyptus grandis / urograndis

Descrição: Eu Grandis
Índice de Sítio: 30,0
Densidade (árvores por hectare): 1667
Porcentagem de sobrevivência (1º ano): 75 %

Idade	Alt. Dominante	Árvores/Ha	Diâmetro Médio	Alt. Média	Área Basal	Volume Total	I.M.A.	tCO2
1	5,4	1249	3,3	4,4	1,0	1,8	1,8	1,7
2	12,2	1248	8,6	9,9	7,3	28,1	14,1	26,5
3	17,4	1245	12,2	14,1	14,5	79,7	26,6	75,0
4	21,5	1239	14,6	17,5	20,7	141,2	35,3	133,0
5	24,8	1231	16,3	20,2	25,8	203,5	40,7	191,6
6	27,6	1220	17,7	22,5	29,9	262,0	43,7	246,7
7	30,0	1208	18,7	24,4	33,1	315,2	45,0	296,8
8	32,1	1195	19,5	26,1	35,6	362,7	45,3	341,5
9	33,9	1182	20,1	27,6	37,7	405,0	45,0	381,3
10	35,5	1168	20,7	28,9	39,3	442,3	44,2	416,5

Equação de Sítio: Embrapa (IS 7 anos)
Equação de Volume: Embrapa
Equação de sortimento: Embrapa
tCO2 = (Vol+25%)x(Dens. Básica: 0,49)x(C: 0,42)x(CO2: 3,66)

SORTIMENTO PARA ÁRVORES REMOVIDAS NO CORTE FINAL (10 ANOS)

Classes DAP	Árv/ha	Altura Média	Volume Total	Sawmill	Energy
12,0-16,0	123	25,7	22,3	0,0	22,2
16,0-20,0	456	28,1	128,4	46,3	81,5
20,0-24,0	392	29,4	166,8	119,0	47,1
24,0-28,0	168	30,4	101,2	87,4	13,5
28,0-32,0	29	31,4	23,1	21,0	2,1
Totais		**28,9**	**442,3**	**273,6**	**166,5**

Figure F.1 – Growth and production tables output from SisEucalipto software.

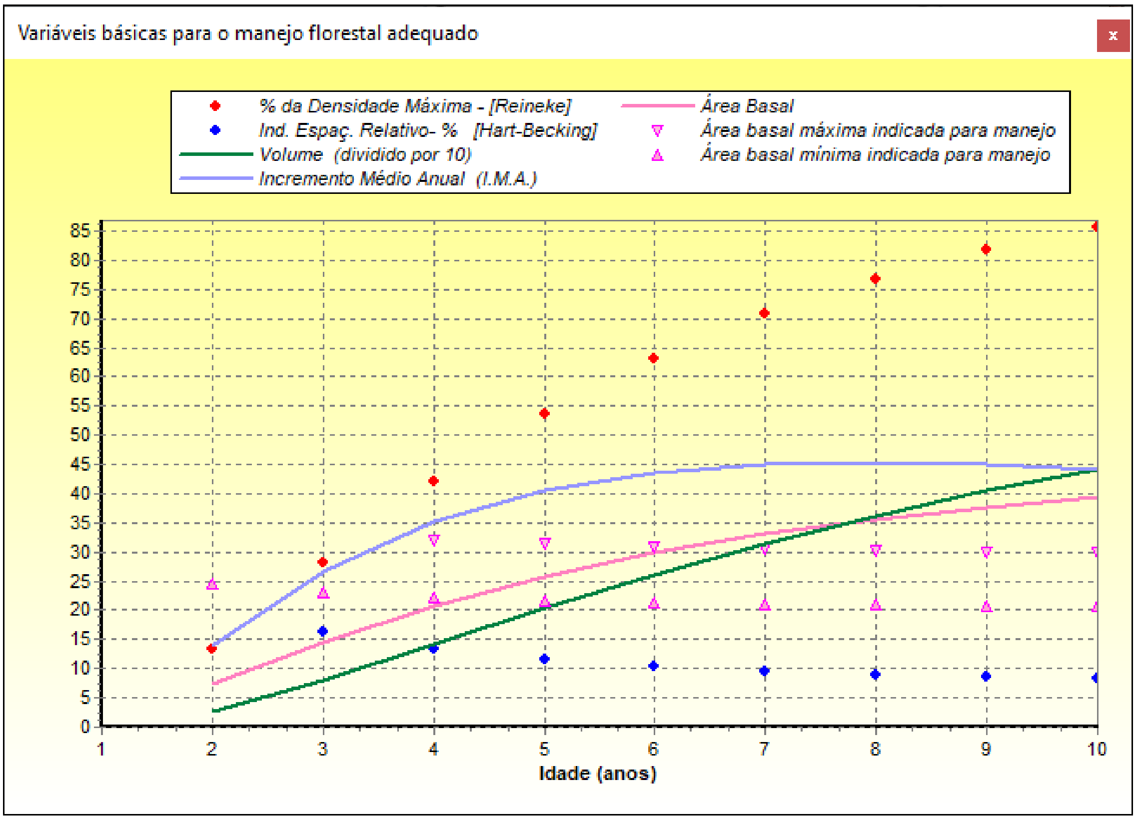


Figure F.2 – Graph with the basic variables for proper forest management generated by SisEucalipto.

Sis.ILPF

TABELA DE CRESCIMENTO E PRODUÇÃO - Eucalyptus grandis / urograndis

Descrição: Integrated Livestock-Forestry
Índice de Sítio: 30,0
Densidade (árvores por hectare): 312
Porcentagem de sobrevivência (1° ano): 75 %

Idade	Árvores/Ha	Altura Média	Diâm. Médio	Área Basal	Vol. Total	Vol. / Ano	t. CO2	Kg. Metano / Ano
1	234	4,8	3,2	0,2	0,4	0,4	0,3	10,0
2	234	10,9	12,3	2,8	11,7	5,9	9,2	164,1
3	234	15,6	19,0	6,7	40,4	13,5	31,7	377,3
4	234	19,3	23,5	10,1	76,0	19,0	59,6	532,2
5	234	22,2	26,5	12,9	111,8	22,4	87,7	626,5
6	234	24,8	28,6	15,1	145,3	24,2	114,0	678,7
7	234	26,9	30,2	16,8	175,9	25,1	138,0	704,1
8	234	28,7	31,5	18,2	203,5	25,4	159,7	712,9
9	233	30,4	32,4	19,3	228,4	25,4	179,2	711,2
10	233	31,8	33,2	20,2	250,9	25,1	196,8	703,0

Equação de Sítio: Embrapa (IS 7 anos)
Equação de Volume: Embrapa
Equação de sortimento: Embrapa
tCO2 = (Vol+25%)x(Dens. Básica: 0,35)x(C: 0,49)x(CO2: 3,66)

SORTIMENTO PARA ÁRVORES REMOVIDAS NO CORTE FINAL (10 ANOS)

Classes DAP	Árv/ha	Altura Média	Volume Total	Sawmill	Energy
28,0-30,0	1	28,9	0,7	0,7	0,1
30,0-32,0	14	30,0	11,9	11,0	0,9
32,0-34,0	64	31,0	61,4	56,1	5,2
34,0-36,0	97	31,8	105,4	99,8	5,4
36,0-38,0	49	32,5	60,0	56,4	3,6
38,0-40,0	8	33,1	10,8	10,5	0,3
Totais		**31,8**	**250,9**	**234,5**	**15,5**

Figure F.3 – Growth and production tables output from SisILPF software.

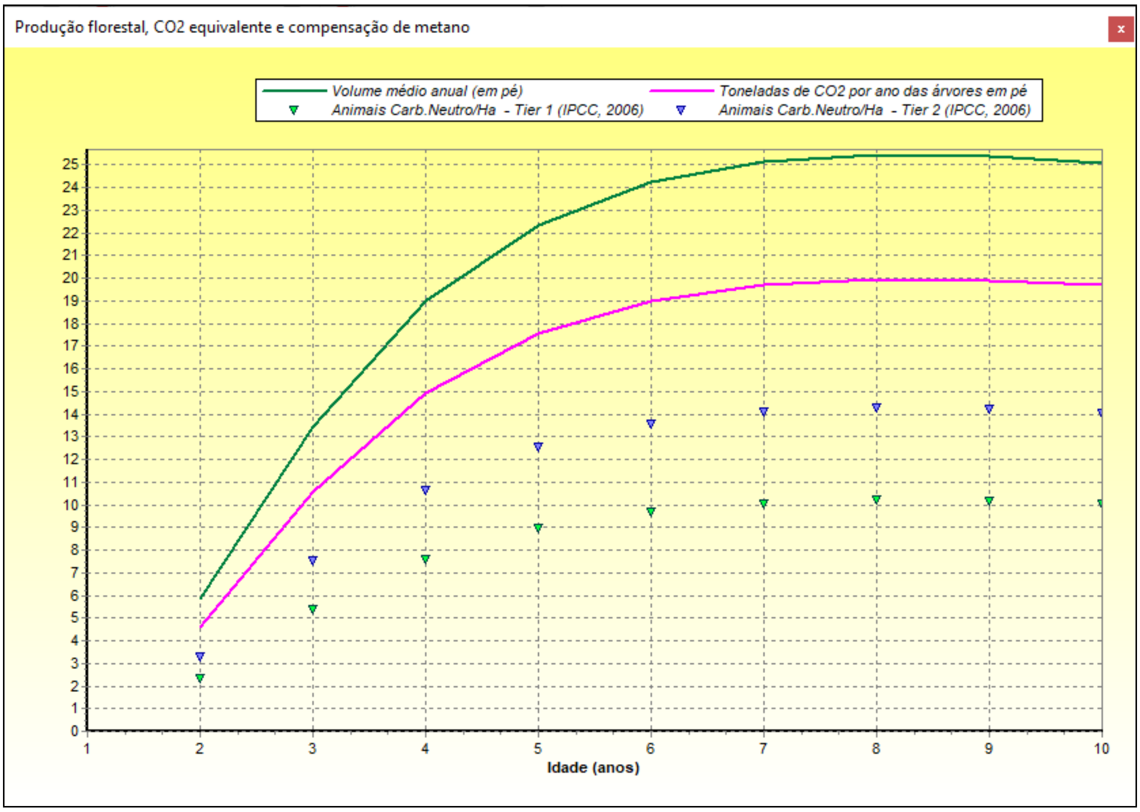


Figure F.4 –Graph of forest production, CO2e and CH4 compensation generated by SisILPF.

2019

A GIS approach to sustainable livestock planning from carbon dynamics analysis
Case study of a cattle ranch in Serra da Mantiqueira (Brazil)

Alexandre Dargains Auricchio de Oliveira

C&SIG

UNIGIS PT

NOVA IMS Information Management School